Case Studies in the Digital Fabrication of Open-Source Consumer Electronic Products

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Abstract

This thesis explores the effects of digital fabrication on the design, production, and customization of consumer electronic devices. It does so through a series of three case studies – a radio, a pair of speakers, and a computer mouse – that combine a custom electronic circuit board with a digitally-fabricated (laser-cut or 3D-printed) enclosure. For each case study, the thesis describes the construction and prototyping of the product and a workshop in which participants modified the design and made the device for themselves. This customization was enabled by the sharing of the design files for the products following the principles and practices of open-source.

The case studies are used to draw practical lessons about the application of electronics, the laser-cutter, and the 3D printer in the digital fabrication of consumer electronic products. Implications are drawn for the open-sourcing of each of these elements and for the software tools used to the design them. The case studies also illustrate four modes of production that digital fabrication enables for electronic devices: one-off, artisanal, kit, and a hybrid mass/custom production. Additionally, they shed light on the types of customization and the human roles that digital fabrication implies for consumer electronics. Three main themes emerge: diversity in design and production, personal connection with devices, and leveraging of the power of software for the making of hardware.

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Contents

1. Introduction

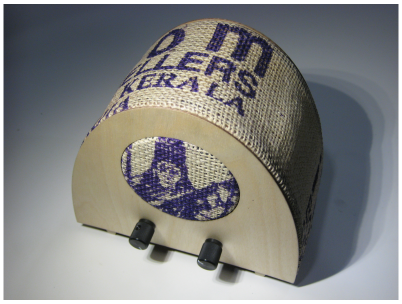
Digital fabrication is changing the way we make things. New technologies like laser cutters and 3D printers make it possible to produce one or more instances of a physical object directly from digital design files. To make another object, you send another file to the machine – and it can be different every time. By eliminating costly, time-consuming tooling, digital fabrication removes the need for large up-front investments and the high production volumes required to recover them. This promises new possibilities for one-off or low-volume production. Digital fabrication technologies work with a wide range of materials – from wood to metal, plastic to fabric, glass to paper – offering possibilities for forms and aesthetics beyond the ubiquitous plastic of most consumer electronic devices.

Despite their small volumes, these digital fabrication processes are not based on the same manual labor and individual skill as traditional crafts. Because the object is produced directly from a digital file, anyone with access to the file (and the fabrication machine) can make a copy of the object. They can also modify an individual part of the object's form without having to recreate the entire design. In a sense, the design file is the object's source (in the sense of "source code") and sharing these files with others can be seen as a as a form of open-source. This open-sourcing of physical objects offers potential for distributed production, for customization and personalization, and for learning about the construction of objects by studying or making their designs.

This thesis explores the possibilities that digital fabrication offers for the production of consumer electronics. It asks a number of questions about how this technology will affect the people and processes involved. How can the circuit and enclosures of electronic devices be designed for production with digital fabrication processes? How will digital fabrication affect the makers and consumers of electronic products and the relationships between them? What kinds of customization are enabled by the flexibility of digital fabrication? What implications does digital fabrication have for the overall landscape of electronic devices?

I explore these questions through a series of three case studies, each of which combines a custom electronic circuit board with a digitally-fabricated enclosure. Two of the case studies – an FM radio receiver and a pair of portable speakers – use a combination of laser-cut plywood, veneer, and fabric. The third, a computer mouse, is housed in a 3D-printed plastic enclosure. These devices were not intended for commercial production and sale but rather to elucidate the general principles and practices that underly the application of digital fabrication to consumer electronics. The design and building of the products tested the feasibility of various constructions and processes.

For each case study, I conducted a workshop in which participants customized the products and made them for themselves. This process yielded information about the skills and motivations underlying the customization of devices, and the ways of doing so.


Case Study #1: Fab FM


Case Study #2: Fab Speakers


Case Study #3: 3D-Printed Mouse

Overall, the case studies offer many lessons for the digital fabrication of consumer electronics. Some are practical, related to the specific processes and tools involved. Others are more theoretical, potential methods for wider production and distribution of devices using the technologies. In general, they suggest possibilities for alternatives to today's mass production of consumer electronics and provide examples of what that could mean for both the products and the people involved in their creation and use.

The following chapter provides technological background for the thesis. The next chapter describes related research work. Then, for each case study, I detail the structure and composition of the product, the design and prototyping process, the workshop, and a potential model for the broader dissemination of the product. The subsequent chapter discusses the best practices, challenges, and difficulties brought out by the case studies. This leads to a chapter outlining the new modes of production for consumer electronics that are enabled by digital fabrication. Then, a chapter discusses the broader implications and themes of the work. The last chapter concludes with a brief sketch of how these processes and products affect the broader landscape of consumer electronics.

2. Background

A number of technologies and practices provide the context for this thesis. They include digital fabrication, electronics production, open-source software and hardware, and online communities, which together raise broader questions about the nature of making.

Mass Production, Craft, and Digital Fabrication

Digital fabrication is challenging the assumptions that underly mass production. It enables individual variation, but of a different kind than handcraft. A comparison of craft, mass production, and fabrication raises deep questions about the relationships between human and technological capability, questions that form the broad intellectual background for this thesis. What does it mean to make something if the object is produced by a machine? How does the variation of handmade goods differ from that of digitally-generated objects? What is the value of human labor in a product? How can objects be tailored for their specific context of use and production?

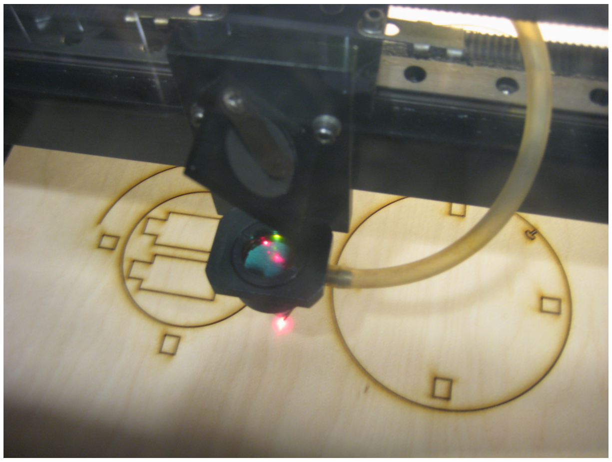
These issues are skillfully analyzed in two books, *Abstracting Craft* [McCullough 1998] and *The Alphabet and the Algorithm* [Carpo 2011]. In the former, McCullough discusses the creation of 3D digital models as a form of craft, involving the hand and eye, manual skill, and iterative construction. While the final file can easily be copied, McCullough notes the difficulty of recreating it any other way, stressing the importance of the human skill and labor in its creation. Carpo emphasizes the differences between craft production and digital fabrication, while contrasting both with mass production. He discusses the ways in which the separation of design and production enabled by industrialization strengthened the notion of authorship of objects, identifying it with the maker of the design, not of the final object. Both craft and digital fabrication blur these distinctions by allowing for the gradual evolution of a design through the work of many people. Carpo also discusses seeming paradoxes in the nature of the reproduction of objects and digital information. The former can be mass-produced, stamped from a single mold, each with slight but almost undetectable variations. The latter can be copied exactly, with no loss of detail but with easy opportunity for large or multitudinous variation.

This thesis explores these issues through concrete examples – the design and construction of three case studies and the process of having people customize and make them. In particular, it provides some examples of the relationship between digital design and physical craft, and the skills, tools, and processes associated with each. Still, in large part this work only reinforces the many questions raised by digital fabrication and its relationship to craft and mass production.

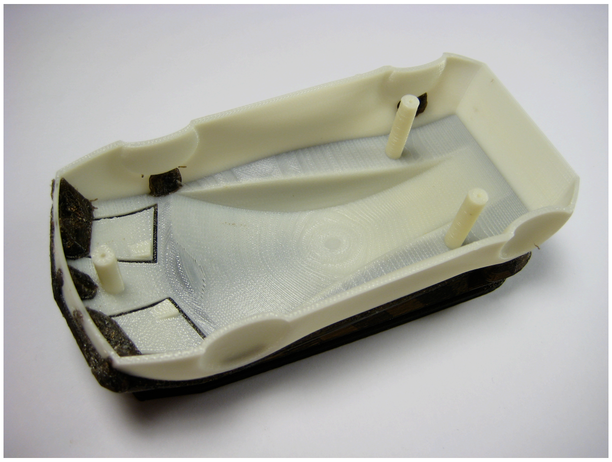
Digital Fabrication

Digital fabrication refers to a set of technologies and processes in which digital information directly drives the cutting, joining, or other manipulation of physical materials to achieve a particular form or structure. Digital fabrication has a number of advantages compared with other manufacturing processes. The absence of tooling reduces setup costs and time. By avoiding molds, digital fabrication allows for more flexibility and freedom in the shapes produced. It tends, however, to have higher per-unit costs and production time compared with traditional mass production processes like injection molding. As a result, it's primarily used for prototyping or for small-volume production runs.

There are two main classes of digital fabrication machines: subtractive and additive. Subtractive machines work by removing portions of a material to leave behind a desired shape or structure. Some, like computer-numeric controlled (CNC) milling machines and routers, work in three dimensions, moving a spinning cutting tool in precise paths to contour a sheet or block of material. This process is known as computer-aided manufacturing (CAM) and is used to produce forms from materials like metal, wood, wax, and foam. Other subtractive machines, like laser cutters and water-jet cutters, work primarily by cutting through flat sheets of material, creating precisely-outlined shapes. Laser cutters works with a variety of materials, including wood, paper, cardboard, fabric, and plastic. In addition to cutting through the material, the laser can be used to etch or engrave lines and patterns on its surface.



Laser-cutting plywood.



3D-printed part from an FDM machine, before removal of support material (in brown).

Additive machines, commonly known as 3D printers, work by building up a form through successive application or fusion of material, a process known as rapid prototyping [Noorani 2006]. There are a variety of 3D printing processes. The first to be commercially available was stereolithography, which was introduced by 3D Systems in the late 1980's. It works by curing a photopolymer, using UV light to turn precisely-traced portions of a liquid bath solid. By incrementally lowering the model into the vat of liquid polymer before tracing the next layer, it cure successive layers together to form the desired 3D form. Selective laser sintering (SLS) is a similar process in which a laser sinters successive layers of powder. After one layer is complete, the machine spreads an additional thin layer of powder on top of it. Then this new layer is sintered with the laser, fusing with the previous one and causing the gradual buildup of the 3D form. In another process, known as fuse-deposition modeling, a thin filament of ABS plastic is melted by an extrusion head whose position is precisely controlled by the computer. Parts are built up as the head traces subsequent layers of the desired form. Typically, another material is used to support the model as it's printed and removed later (e.g. by dissolving it with a solvent). Other 3D printing systems use a head similar to that found in an inkjet printer to deposit layers of model and support material.

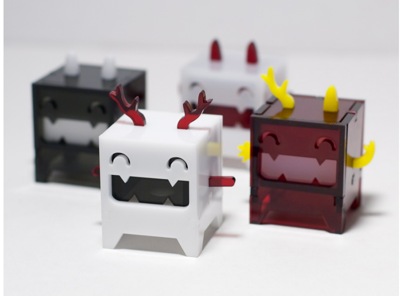
A variety of software tools can be used to design forms for production on digital fabrication machines. This process is generally known as computer-aided design (CAD) and includes a variety of 3D modeling packages like Rhino, SolidWorks, and Catia. For cutting machines like the laser-cutter, two-dimensional drawing programs like Adobe Illustrator or the open-source Inkscape can also be used to generate forms for fabrication.

In recent years, digital fabrication has become increasingly accessible to a wider range of people and purposes ([Gershenfeld 2005] and [Lipson 2010]). This is often called personal fabrication. Falling costs for traditional fabrication machines, and the emergence of low-cost do-it-yourself (DIY) machines, has made it feasible for individuals or small businesses to purchase their own machines. Popular low-cost 3D printers include the MakerBot and RepRap, both of which use an FDM extrusion process (although without support material). Community centers like the FabLab network or TechShop offer access to shared digital fabrication facilities. Online services like Shapeways and Ponoko offer on-demand fabrication to individual consumers. This increased accessibility creates new possibilities for personal or small-business creation with digital fabrication [Anderson 2010]. A recent report commissioned by the U.S. Office of Science and Technology Policy [Lipson 2010] calls for many steps to disseminate fabrication, including "put a personal manufacturing lab in every school".

There are numerous examples of small businesses using digital fabrication for the production of consumer products. Freedom of Creation uses 3D printers for production of lamps, furniture, and personal accessories. Nervous System makes jewelry and housewares with 3D printers, laser cutters, and other fabrication processes. Wood Marvels sells wooden toys composed of laser cut wood, using Ponoko as a fabrication service and showroom. Vambits are small plastic figures also fabricated by Ponoko and sold on-demand. Particularly when an outside service is used for the production, digital fabrication allows these companies to start with a minimum of start-up capital or investment.

3D-printed (SLS) lamp from Freedom of Creation.

3D-printed (SLS) bracelet from Nervous System.



Laser-cut vambits from Drownspire.

Electronics Production

Circuit board fabrication is a mature and widespread digital fabrication technology [Khandpur 2006]. In this thesis, I discuss it separately from laser-cutting and 3D printing (which I'm calling "digital fabrication") because it tends to accompany and complement them in the construction of the case studies. Printed circuit boards (PCBs) are produced using photographic processes that can scale to many different production volumes, from one or a few boards to hundreds, thousands or more. Many producers offer online ordering, standard pricing, and clear performance specifications, allowing individual customers to purchase boards without an explicit negotiation or specification process. The per-unit cost falls with volume, but these services allow for small orders. This combination of low initial investment of both time and money greatly reduces economic and procedural barriers to entry.

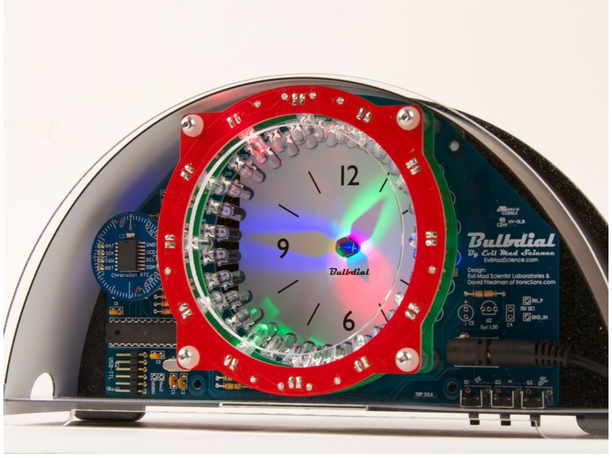
A variety of free- and low-cost circuit design tools are available for the creation of simple boards. For example, Eagle is a commercial package that offers a freeware version for two-sided boards within in a certain maximum area. It was used for the case studies in the thesis. Open-source alternatives include packages like Kicad and Geda. While professional tools remain too complex and expensive for most hobbyists or individuals, the accessible alternatives are capable of producing a range of functional designs.

Many electronics components are also widely available to individual customers. Distributors like Digi-Key in the U.S. and Farnell in Europe offer many thousands of components in quantities from one and up. Online ordering and up-front pricing makes it possible to purchase components without a pre-existing business relationship or a lot of money. Detailed search criteria and documentation (as well as the standardization of the parts themselves) allow for the discovery and selection of appropriate components. These distributors may not provide quite the same range of products or low prices available to industrial customers, but they offer the supplies needed for a variety of applications and production volumes.

PCB assembly services (for soldering the components onto the circuit boards) are not yet as standardized and streamlined as circuit board fabrication and component distribution. While many suppliers offer a range of services for varying volumes, the process still requires explicit negotiation and specification. On the other hand, PCB assembly is a relatively accessible process for low volumes. Hand tools or simple machinery (e.g. hot plates) allow for soldering of tens or hundreds of boards. Or, products can be provided as kits containing circuit boards and components to be soldered together by the customer.

There are many current examples of businesses creating and selling electronic kits or modules for individual or hobbyist use. One prominent example is SparkFun Electronics, which carries modules for a large variety of sensors and actuators, as well as a range of microcontroller development boards and other components and supplies. SparkFun also operates a PCB fabrication service, BatchPCB, which pools designs from multiple users to provide low prices for small quantities of boards (albeit with a longer turn-around time – a few weeks – than other services). Adafruit Industries and Evil Mad Scientist Laboratories offer a number of hobbyist electronic kits, including devices like clocks, LED displays, and microcontroller development boards. These two companies practice open-source hardware, providing complete design files for their products, as, to a lesser extent, does SparkFun.

Assembled TV-B-Gone kit from Adafruit Industries.



Assembled Bulbdial Clock kit from Evil Mad Scientist Laboratories.

Open-Source Software & Hardware

The practice of publicly sharing the source code for computer programs is described with two main terms: free software and open-source. The Free Software Foundation emphasizes the freedom of the user of a program to:

- run the program for any purpose,
- study and change how the program works,
- redistribute copies, and
- distribute copies of modified versions of the program. [FSF 2011]

The open-source definition [OSD 2011], in contrast, specifies the legal restrictions that may be imposed by the license applied to a body of source code. It emphasizes clarity of the permissions granted by the license so the source code can be used and modified without explicit negotiation or agreement. In particular, it seeks to ensure that the rights granted by the license apply equally to all, regardless of their individual affiliations or applications. This generates a commons of software that can be combined and built upon for a variety of purposes, whether or not they were foreseen by the original authors of the code. Although there are many open-source software licenses, sometimes incompatible, the clear standards offered by the open-source definition enable widespread cooperation from a diversity of individuals, companies, and other organizations.

For the purposes of this thesis, it's important to abstract two main principles from the specific legal mechanisms of open-source software. These are expressed by the words themselves: "open"-ness and "source"-ness. To take the latter first, source-ness is the idea that the final, functional object (in this case, a working piece of computer software) can be derived from the original digital design files (the source code) in a straightforward and reproducible way. That is, the source code embodies the majority of the human creativity and effort that has gone into the creation of the software. The openness refers to the rights expressed by the free software and open-source definitions. Combined, these two principles mean that it is possible for anyone to derive their own version of someone else's creative output by simply editing the source to make the desired changes. You don't have to acquire their skills, understand the whole of their effort, or have any direct contact with them to build on their work.

These underlying principles and practices of open-source are beginning to be translated to hardware. As a result of the digital fabrication processes discussed above, it's possible for someone to take a digital design file, modify it, and produce a new object from the modified design. That makes it useful to share those design files. This sharing has led to the practice of open-source hardware [Thompson 2008], which borrows much philosophy and practice from open-source software. Recent efforts include the drafting of a definition for open-source hardware [OSHW 2011] and the holding of an Open Hardware Summit. Many companies make and sell open-source hardware, including SparkFun Electronics, Adafruit Industries, and Evil Mad Scientist Laboratories, as mentioned in the electronics production section above. Some makers of mass-produced consumer electronics also release the designs for their products as open-source hardware, including the Chumby wifi device, the OpenMoko cell phone, and the NanoNote palmtop computer. The MakerBot and RepRap 3D printers mentioned above are also open-source hardware, with complete plans available for download.

The case studies provide an opportunity to examine the practice of open-source hardware in the context of consumer electronics. While plans are available for both the hobbyist kits and mass-manufactured products mentioned in previous paragraph, there has yet to be research that looks at the ways that people actually modify or make use of them. By having people take open-source hardware designs, customize them, and make devices from them, the workshops conducted during this thesis yield practical lessons and principles for open-source hardware.

Online Communities

A number of online communities provide information and support for high-tech hobbyists and others who are likely to be interested in the digital fabrication of consumer electronics. Make Magazine, a quarterly publication, hosts a website with an extensive blog linking to a wide variety of electronics projects and tutorials. Instructables features how-to articles contributed by a variety of users on a huge range of topics, including many related to electronics and digital fabrication. Thingiverse provides freely downloadable models for production with fabrication machines – primarily 3D printers but also laser cutters and other machines.

Other sites support the commercial aspects of independent or small-scale makers. Kickstarter is a platform that allows individuals or groups to raise money for a particular project. People donate in exchange for benefits set by the person posting the project (e.g. pre-ordering a particular product). The transactions are only completed, however, if the project reaches total funding pre-defined by its originator. That way, they are only obligated to fulfill their pledges if they receive enough money for the initial capital required to kickstart their project. Etsy provides a marketplace for handmade objects, providing their makers with a commerce platform and connecting them to potential customers. Both of these could potentially support the commercialization of digitally fabricated electronic products like the ones developed in this thesis.

3. Related Work

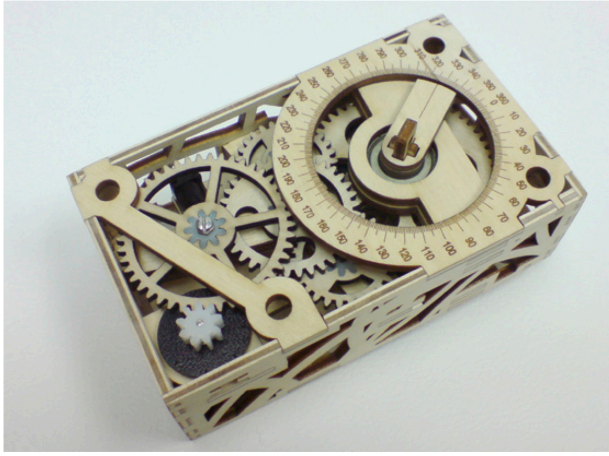
This chapter highlights prior research that explores themes similar to those of the thesis.

Combining Electronics and Digital Fabrication

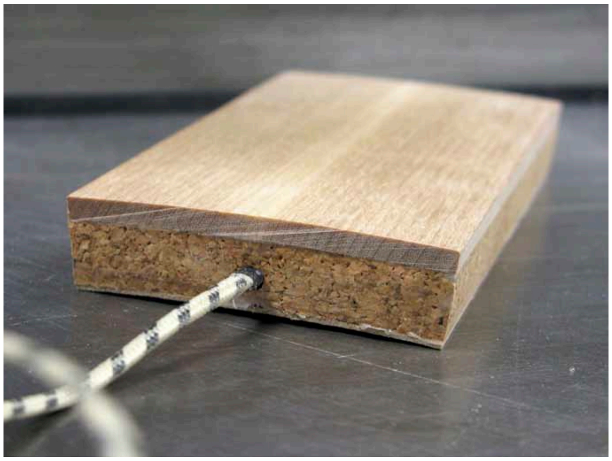
A number of research projects have combined electronics with digitally-fabricated parts in the construction of prototypes. They provide motivation, design principles, and aesthetic inspiration for the case studies in the thesis.

Many computational toolkits have employed digital fabrication for the construction of their modules, illustrating the feasibility of these production processes for electronic devices. Topobo [Raffle 2004], an actuated construction kit, used digital fabrication to create prototypes for user-testing. The servo-motor based circuits were enclosed with 3D-printed parts and these were connected with laser-cut wood. Research focused on interaction with and use of the construction kit, with digital fabrication serving primarily as a means to produce the prototypes. Another construction kit, TOPAOKO [Wu 2010], explicitly targets user creation of the toolkit itself. Its component cubes are made from laser-cut hardboard, together with a PCB, electronic components, copper tape, and magnets. The preliminary report, however, does not describe attempts by users to build the kits. Molecubes [Zykov 2007] is an open-source modular robotics kit that uses 3D-printed parts to house electronics. Again, though, the initial paper doesn't discuss modification or use of the design files by others. Still, these toolkits demonstrate an awareness of the possibilities that digital fabrication offers for sharing design files so others can construct devices for themselves.

Other research focuses explicitly on the design processes and aesthetic possibilities enabled by the combination of electronics and digital fabrication. Plywood Punk [Schmitt 2009] uses the construction of a wooden servo motor to illustrate a number of design principles for animated artifacts. The servo is constructed from a DC motor, microcontroller, laser-cut plywood and delrin, and other minor electronic and mechanical parts. The circuit is soldered around a wooden template without use of a traditional PCB. In discussing the device, the authors propose four design principles: iteration, exploring material properties, engaging the performative aspects of the design, and crossing disciplinary boundaries. Wooden Logic [Cottam 2009] focuses more specifically on the material qualities of wood, using the laser-cutter and traditional wood-working in combination with pre-existing electronic components and circuits. In one investigation, sensors are integrated into wood and cork housings to create three objects which have no visible electronics but nevertheless function as circuit elements. In another, device pairs communicate with each other wirelessly and can be mated with a dovetail joint. These objects respond with sound and vibration when in the presence of the corresponding member of the pair. Six identical pairs were subjected to various processes of wear, including aging in salt water, chewing by a dog, painting, sandblasting, etc. The resulting objects illustrate unique, aged appearances not often seen in electronic devices.



Plywood servo motor [Schmitt 2009].



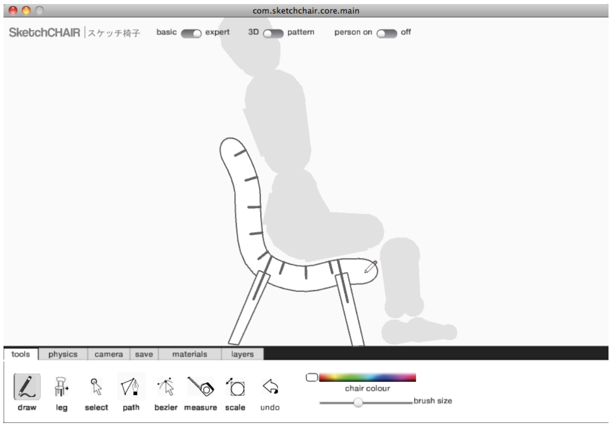
Force sensor in cork and wood [Cottam 2009].

Another project [Saul 2010] demonstrates possibilities for the combination of electronics with another medium, paper. The authors describe the design and construction of three interactive paper devices: robots, speakers, and lamps. They include unusual techniques for integrating electronic circuits and components with paper – for example, gold leaf circuits, sewn shape memory alloy wires, magnets, etc. The shapes of paper itself are variously formed by the laser cutter, computer-controlled cutting machines, and with manual knives. The authors also discuss custom software tools that make it easier to design the objects to satisfy functional or aesthetic criteria.

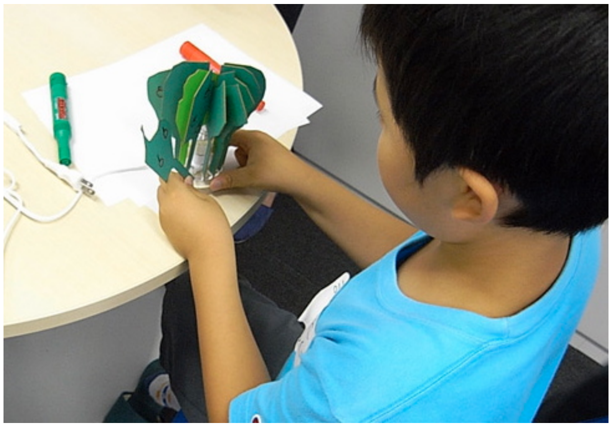
Extending the Audience for Digital Fabrication

Human-computer interaction (HCI) researchers have built and tested a variety of custom tools intended to make digital fabrication accessible to a wider audience. In [Eisenberg 2008], the authors list three potential motivations for this application of digital fabrication to education: ornamentation and decoration, personal expression, and intellectual development. This thesis pursues an alternative to the strategy of creating custom tools, instead using open-source hardware designs together with existing CAD software to enable end-user customization. Still, these studies offer important insights into the motivation and ability of individuals to make use of digital fabrication technologies. They also suggest a natural direction and provide guidance for future work: the creation of custom software tools for designing and customizing electronics devices like those explored in the case studies.

Many of these tools for digital fabrication focus on a particular design domain. MachineShop [Blauvelt 2006] is a software package for designing mechanical automata. It includes interfaces for designing components like gears and cams based on a desired motion and materials. These are then fabricated on the laser cutter. The authors worked with six children (aged 10 and 11) over an extended period, meeting roughly once a week for four to nine months – long enough to create one or two automata. They describe an in-depth process of brainstorming, prototyping, and testing various designs and discuss the resulting increase in knowledge of automata and their mechanisms. In another example of domain-specific design tools, [Oh 2006] describes two programs: one for designing toy wooden skeletons of dinosaurs, and the other for model furniture. Both produce shapes that can be laser-cut from wood or foam core and press-fit together. They take input in the form of sketches by the user (with a digitizing tablet) and use it to generate the final geometry, including joints. SketchChair [Saul 2011] is a software tool for designing chairs constructed from flat parts. It includes a physics engine for simulating the behavior of the chair in gravity and the ergonomics of someone sitting in it. SketchChair can be used with fabrication machines at a variety of scales, including paper cutters, laser cutters, and CNC routers. In a workshop trial of SketchChair, all participants successfully produced miniature chairs. Furthermore, they expressed a preference and increased value for chairs they designed themselves versus purchasing existing ones.



The SketchChair interface [Saul 2011].



Assembling a Spatial Sketch lamp [Willis 2010].

Spatial Sketch [Willis 2010] takes the notion of a custom interface even further, using infrared cameras to track a user's motions in space. These motions are turned into a 3D form, which is then sliced into flat shapes, cut out on the laser cutter, and assembled into a lamp shade. User testing revealed difficulties with sketching in 3D, with or without on-screen feedback. Still, in a workshop 8 to 11 year old users sketched and assembled lamps from card-stock, then decorated them with markers. CopyCAD [Follmer 2010] presents another approach to tangible interfaces to CAD. In this case, a projected display and interaction surface augment the material stock in a CNC milling machine. FlatCAD [Johnson 2008] takes yet another approach, allowing users to write programs that generate geometry for fabrication.

All of these tools show that it is possible for a variety of users to design, customize, and build their own objects using digital fabrication. These activities lend themselves to a variety of tools and materials, types of customization, and learnings. In the next chapters, the case studies will explore some of these same themes, using open-source hardware rather than new software tools to provide a basis for more accessible creation and customization.

Digital Fabrication in Architecture

Digital fabrication has an established history in architecture – both for the creation of models during the design process and the manufacturing of elements of the final structure or building [Sass 2006]. Researchers have explored a variety of techniques for designing and assembling larger structures from fabricated parts. For example, [Sass 2007] discusses software for automatically generating the joint geometry needed to assemble flat sheets of CNC-cut plywood into a house. It also describes the use of laser-cut cardboard for prototyping these assemblies. In another example, [Kilian 2003] discusses techniques for creating curved forms from flat sheets of CNC-cut material.

Do-It-Yourself (DIY) Culture and Technology

In [Kuznetsov 2010], the authors provide an overview of six online DIY communities, discussing the motivations and practices of their participants. Respondents to their survey listed, as their reasons for contributing to DIY projects, a desire to express themselves and be creative, to learn new skills, to make things they can't buy, and to personalize their things. When asked about their motivations for contributing to online DIY communities, respondents listed getting inspiration for future projects and a desire to learn new concepts as the main factors. The authors discuss four main themes emerging from their research: a low barrier to entry (and cross-pollination between different activities), learning, creativity, and sharing. These resonate strongly with my motivations for pursuing the work of this thesis. Additionally, digital fabrication and open-source hardware present interesting possibilities for addressing the three main areas listed as next steps by the authors: integrating physical and digital domains, new forms of knowledge transfer, and supporting iterative studio culture. For these reasons, I think digital fabrication of consumer electronics is a natural fit for and extension of today's DIY communities.

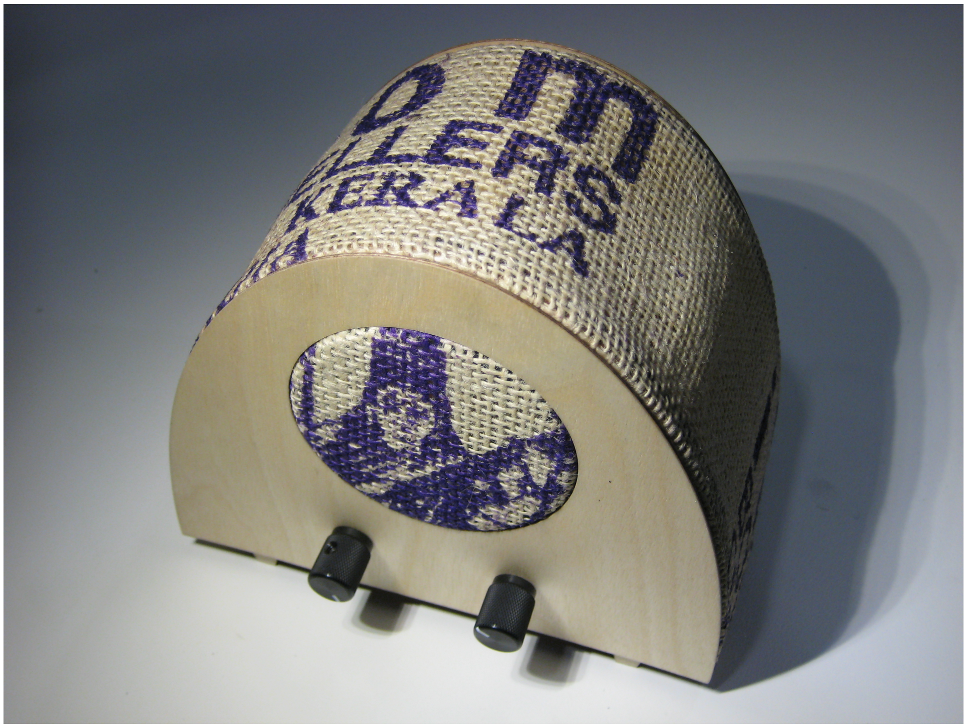
Other work examines specific DIY approaches and technologies. For example, [Buechley 2010] describes how a specific technology can foster a new community of DIY practitioners. In this case, the technology is the LilyPad Arduino, a microcontroller module that can be sewn into clothing with conductive thread. The dissemination of the LilyPad generated a female-led hobbyist electronics community creating projects very different from those found in more traditional electronic hobbyist groups. In a very different example, [Moriwaki 2006] describes the use of found and recycled materials together with hobbyist electronics to create improvised musical controllers. They emphasize non-traditional processes as a way of engaging beginners and providing freedom for exploration and creativity. A workshop at CHI 2009 [Buechley 2009] provided an opportunity for interested practitioners to discuss the methods, communities, and values of the HCI and DIY practitioners.

Two papers on the GoGo board, [Sipitakiat 2002] and [Sipitakiat 2004] provide an illustrative example of an attempt to design a low-cost circuit board for global use. They emphasize the importance of component selection, including use of widely available microcontrollers and easy to solder packages. In particular, the board was designed to use only components available from electronics markets in Brazil, and those at a cost of less than $20 (US), less than their price in the United States. The use of local components not only lowers the parts cost, but also avoids import taxes, which can be substantial for assembled electronic devices. Additionally, it blurs the lines between manufacturer and user of the board by making it possible for users to assemble the circuit for themselves. Although this thesis doesn't explicitly consider international context, the lessons from the GoGo board provide a useful foundation for designing circuits for others to customize or construct.

4. Case Studies

The following three case studies (a radio, a pair of speakers, and a computer mouse) explore the design, making, and customization of consumer electronics using digital fabrication. For each case study, the construction of the product is described, an example of the way a device can be produced from the combination of electronics and fabricated parts. A description of the design and prototyping process provides insights into the ways in which the technologies support iteration and evaluation. For each case study, a workshop offers an evaluation of the ways in which people of different background and skills approach the process of customizing and making a consumer electronic product using digital fabrication. Finally, a potential model for the further dissemination of each product suggests ways they could be made available to a wider audience.

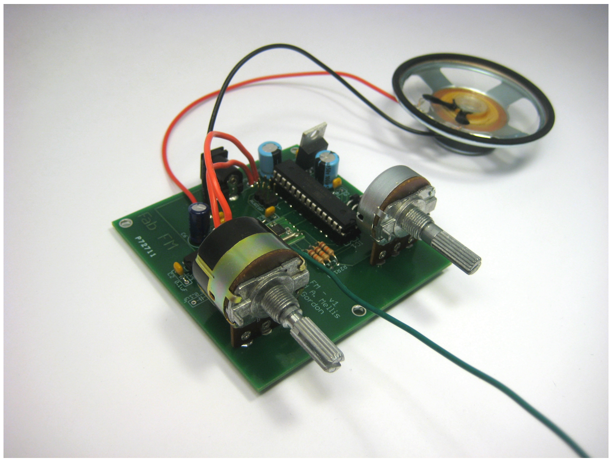
Each case study investigates different opportunities and challenges. The radio and speakers integrate laser-cut materials that lend themselves to craft and customization in the physical domain. The mouse's use of 3D printed parts places greater emphasis on digital customization and 3D modeling in particular. All three product types were selected in part because of their widespread use but also because they involve mature technologies that were amendable to prototyping and implementing in the course of the thesis. Their familiar functionality allowed for a focus on the issues of construction and customization at the core of the thesis.



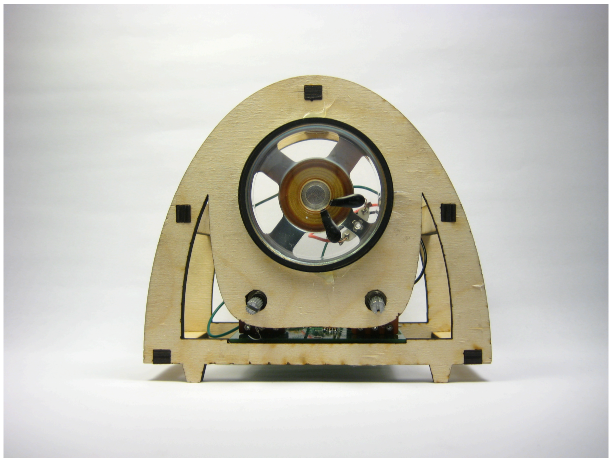
Case Study #1: Fab FM

The Fab FM is a standard FM radio receiver with a custom-designed circuit board and a laser-cut enclosure. Traditional radio is an appealing case because of its familiarity, its technological maturity, and the established but diverse history of radios as products. Radios have a known function but one that offers room for flexibility and creativity in its interface and appearance. As such, it offered a clear basis on which to design a circuit and enclosure while opening up possibilities for customization by others. We tested these possibilities in a workshop in which other modified the design of the radio, altering its appearance and functionality. In order to further disseminate the radio, we're designing it for potential distribution as a kit by SparkFun Electronics and Ponoko.

This case study was initially created in collaboration with Dana Gordon as my final project for professor Neil Gershenfeld's class, "How To Make (Almost) Anything" in the fall of 2009. In addition to testing the overall hypotheses of the thesis, we brought to the project an interest in found or recycled materials and the ways they could be incorporated into the customization of an electronic product.



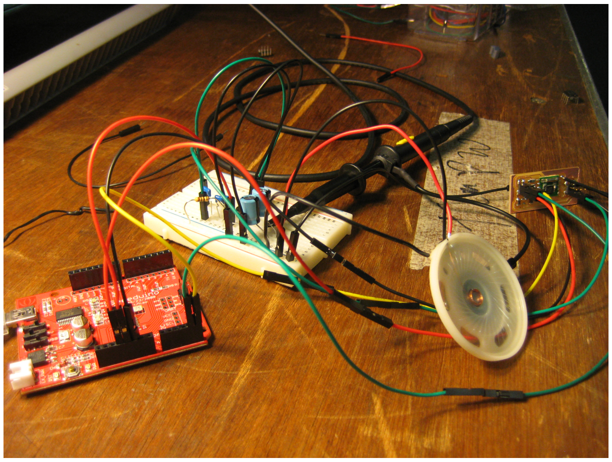
An assembled Fab FM circuit board.



Fab FM plywood frame and electronics.

Construction

At the heart of the radio is a digital FM receiver (the Airoha AR1010) controlled by a microcontroller (ATmega328 AVR from Atmel), whose output is sent through an amplification circuit (based around the LM386) to the speaker. The structure of the radio is provided by a laser-cut plywood frame, with a front and back face held together by press-fit horizontal struts. This technique allows the faces to take on any shape, and we choose a curve to highlight this flexibility. The electronic circuit board rests on a cut-out in the frame. Carefully positioned holes in the front face help to support the knobs, which are soldered to the PCB. The speaker is secured in a circular cut-out by fabric glued to the plywood. The frame is then wrapped with another piece of fabric, paper, or other soft material. Laser-cut veneer or other material is attached to the front and back faces. The laser cut pieces were designed in Adobe Illustrator and Inkscape. The design of the electronic circuit board can be edited with the freeware version of Eagle, a CAD package popular with hobbyists. The radio's firmware can be compiled with the open-source GCC and uploaded via a programming socket on the circuit board.



The initial electronic prototype for the Fab FM (milled breakout board for the FM tuning chip, breadboard amplifier circuit, and Arduino-compatible board).

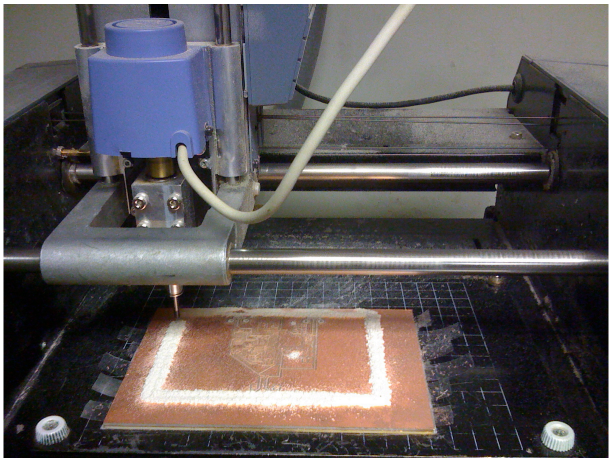
Cardboard and paper prototype of the Fab FM structure. (photo by Dana Gordon)

Initial Design and Prototyping Process

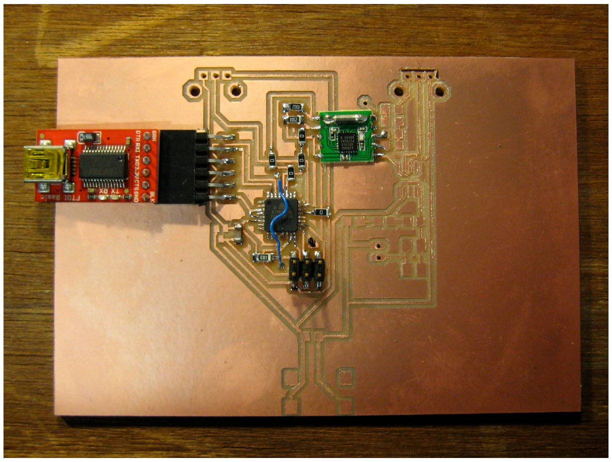
After we decided on the overall concept for the Fab FM, initial design and prototyping proceeded in parallel, with Dana refining the overall form and structural composition of the radio while I developed the circuit. Crucial to our ability to work together was up-front agreement about the desired interface and, consequently, selection of the electronic components which were to protrude through the enclosure. These components – in this case, knobs, speaker, and power jack – shaped the overall form and individual dimensions of the radio's enclosure and provided functional requirements for the circuit.

The main structural challenge was figuring out how to hold the speaker in place and how to integrate the various materials (plywood, fabric, and veneer). We settled on a configuration in which the fabric is glued to the plywood, holding the speaker in place, and then covered with veneer (which is glued onto the front and screwed onto the back). An initial prototype combining laser-cut cardboard and paper with our chosen speakers and knobs (but no functioning circuit) allowed for verification of the construction method, overall form, and some specific dimensions.

The main technical challenge was figuring out how to receive the radio signals and translate them into audio. After evaluating a few possibilities, we selected the AR1010 digital FM radio receiver module – despite its cost (approximately $9 in quantity one) – because of the resulting quality and ease of construction. To test the functionality of the AR1010, I milled a small breakout board for it using a Modela MDX-20. This was controlled by an Arduino-compatible microcontroller development board (Seeeduino) running example code provided by SparkFun (distributor of the AR1010) and the audio output was amplified with a simple op-amp circuit on a breadboard. I then replaced the Seeeduino and breadboarded circuit with two additional milled circuit boards. Testing these allowed me to verify the digital design files (Eagle CAD) on which they were based, making me confident combining them into a single circuit board design.



Milling the final circuit board for the initial Fab FM prototype on a Roland Modela.



Assembling the final circuit board for the initial Fab FM prototype.

After completion of the preliminary prototypes and selection of the basic approaches to the structure and circuit, we proceeded to integrate the two aspects of the radio. This process was complicated by our use of separate design tools for each aspect (Eagle for the circuit board; AutoCAD, Illustrator, and Inkscape for the structure). These programs do not interoperate and so ensuring consistency of coordinates and dimensions between them was a tedious manual process. For example, correctly positioning the holes for the knobs in the front face of the radio requires knowing their location on the circuit board (determined by the Eagle file), their dimensions (from their datasheet), and the thickness of the circuit board itself (measured with calipers). Fortunately, this process was facilitated by the relative ease, speed, and low-cost of laser-cutting physical prototypes of the enclosure (out of cardboard or plywood).

Eventual construction of the integrated prototype proceeded fairly smoothly, probably a result of the numerous preceding tests. We used the milled circuit board, laser-cut plywood parts, fabric from a bag I brought home from a trip to India, and laser-cut veneer. The radio was held together with wood glue and some screws.

Preparation of Kit

In preparation for the workshop (described below), we modified the Fab FM electronics for easier assembly as a kit. This included modifying the circuit board to use larger through-hole (instead of surface-mount) components, as they're considered easier for beginners to solder. We also took advantage of redesigning the board to switch to new knobs, one of which had a built in switch ("click") for turning the radio on and off. These were sourced from a different distributor than the rest of the components.

For the new design, we ordered the circuit board from traditional PCB fabrication services rather than milling them ourselves. This involved two stages: in the first, we used a relatively quick (~1 week turnaround) but expensive ($33 per board) service offered by U.S.-based Advanced Circuits to verify the functionality of the updated board design. Then, we ordered 17 boards from a Chinese manufacturer, Golden Phoenix, at a total cost of $110 and a turnaround time of two weeks. These new circuit boards worked well, but there was a complication with the new batch of AR1010 modules. They didn't work at all (i.e. didn't respond to commands from the microcontroller). To get them to work, I had to hunt down the AR1010 datasheet on an obscure website, then randomly tweak undocumented hex values in the SparkFun sample code (used to initialize the AR1010's registers). Neither the values from the example code nor the datasheet worked, but by testing combinations of the two, I managed to find one that did.

Workshop and Variations

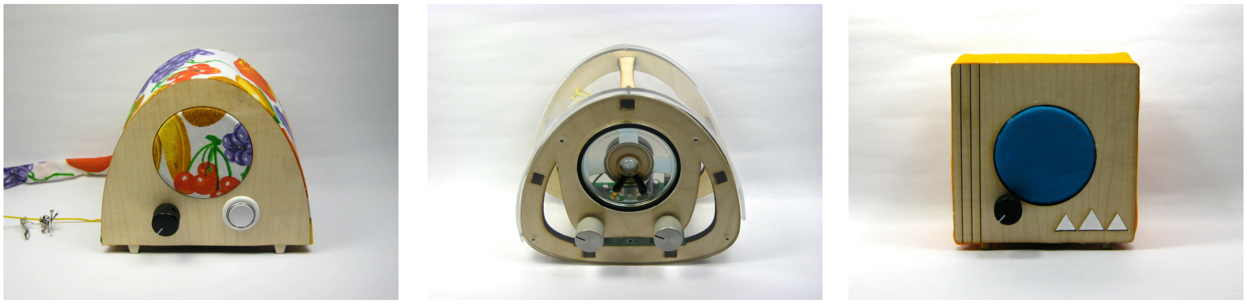
To explore the possibilities for customization of Fab FM, we held a one-day workshop in which participants were asked to design and construct their own variations on the radio. We invited people we thought likely to be especially creative in the modifications; eleven attended (seven men and four women). The workshop was held in the High-Low Tech lab space, which offered access to soldering irons, a laser cutter, and miscellaneous supplies. Each participant was provided with a kit containing the Fab FM circuit board and electronic components; the other materials needed to construct the standard design (e.g. plywood and fabric) were on hand. The workshop began with an introduction to the kit and the sharing of participants' ideas for their radios. Most of the day was spent designing and building Fab FM variants, which were presented and documented at the end of the workshop.

Participants quickly identified ideas for modifications to the design of the radio, including:

- harvesting energy from vibrations caused by sound waves hitting the speaker,
- speaking aloud the frequency of stations as the radio was tuned,
- analyzing the received audio signal in order to tune to a station with particular musical qualities,
- constructing the speaker from laser-cut plywood, a magnet, and an electromagnet,
- a miniature version of the radio that also functions as a nightlight,
- using fabric matching a friend's newly handmade curtains, and

- tuning only to the one or two stations listened to by the intended user.

Although it was a struggle to both customize and build a radio within the day, many participants finished with a solid basis for their own Fab FM variation. Three participants created aesthetic variations on the case: one using curved transparent acrylic to reveal the electronics inside, one miniature version, and one square-shaped design with laser- etched text. Two participants constructed a prototype of the plywood speaker. One participant customized the Fab FM for a particular user, his girlfriend, using a fabric matching her curtains and modifying the radio's software to tune to her two favorite stations. Two other participants also modified the interface to the radio: one replaced the tuning knob with buttons for seeking up and down, while another evenly distributed the available stations across the range of the knob's movement. One participant tweaked the amplifier circuit to find the maximum volume possible without distortion. Another modified the design of the PCB in order to mill it on a CNC machine of his own design and construction.



Fab FM variants created by workshop participants.

Overall, we saw three main dimensions of customization: shape / form, materials, and behavior / functionality. These modifications seem to reflect participants' skills and interests as well as the relative accessibility of various fabrication processes. Given the availability of a laser cutter, participants were able to design, prototype, and construct modifications to the shape of the radio with little assistance. Changes to the materials and appearance were similarly straightforward. Modifying the behavior of the radio, however, was more difficult. Participants were able to customize the physical interface (i.e. knobs and buttons) more-or-less on their own, but the corresponding changes to the code required either a strong background in programming or close assistance.

Dissemination

In order to make the Fab FM available to a wider audience, Dana and I are in the process of redesigning it to suit distribution as a kit from SparkFun and Ponoko. We envision a combination of circuit board, through-hole components, and laser cut parts to which the customer would add their own fabric. They would then solder the circuit board together and assemble and glue the wood and fabric to complete the radio. This process would allow for individual crafting and customization without requiring customer access to a laser cutter or use of any digital design tools. Having SparkFun produce and package the circuit board and electronic components in bulk should allow for savings compared with either us buying and reselling their components or an individual ordering them in single quantities. It's not clear, however, whether Ponoko would achieve or offer economies of scale for repeated production of the same laser-cut parts. It seems likely that the kit would retail for something in the neighborhood of $80.

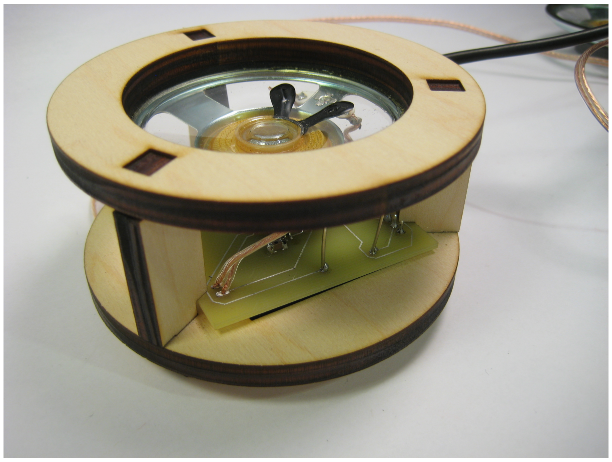
SparkFun has expressed interest in distributing such a kit, but we would need to redesign it to use the electronic components they already stock (e.g. a smaller speaker element and different potentiometers and knobs). Another complication is the absence of veneer from Ponoko's material selection in the United States, which may require a significant redesign of the enclosure. We're also considering replacing the tuning knob with digital (seek) controls. Again, this process is facilitated by the speed of iteration offered by our access to a laser cutter and milling machine, although final verification of dimensions and alignment would likely require testing of samples produced by SparkFun and Ponoko.

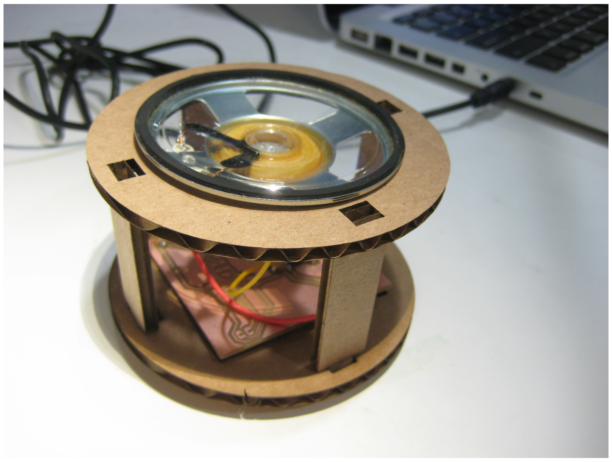
Case Study #2: Fab Speakers

The Fab Speakers are a pair of portable, battery-powered speakers with a construction similar to that of the Fab FM. This case study attempts to simplify as far as possible the design of an open-source consumer electronic product in order to understand how easily and cheaply it can be produced. Additionally, while speakers and amplifier circuits are also a mature and accessible technology, they seem more relevant than FM radio today. The design of the speakers, while containing the same basic element as the Fab FM, went through a number of iterations in order to simplify their construction. They were evaluated through a workshop in which members of the general public made the speakers for themselves. The design of the speakers also lends itself to individual construction by assembling components sourced from various stores and services, although this would be more expensive than centralized small-batch production of kits.

Construction

The circuit board inside the speakers amplifies audio signals using a pair of operational amplifier chips (TPA301D / TPA701D) and some smaller passive components, all surface-mount (i.e. soldered on top of, not protruding through, the circuit board). They are powered by three AAA batteries (4.5 volts), whose holder extends through a hole in the bottom face of the plywood frame. A standard 3.5mm audio cable also comes out the bottom and sound is produced by two 60mm speaker elements. These speaker elements are held against the top face of the plywood frame by laser-cut plywood struts that also connect the top and bottom faces and hold the circuit board in place. The top face of the speakers are covered in fabric and an iron-on veneer strip wraps around their sides. One of the two speaker enclosures contains the circuit board, one of the speakers elements, the batteries, and the audio cables; the other contains just a speaker element, connected to the circuit board in the other housing by speaker cable. As with the Fab FM, the circuit board design was done with the Eagle CAD software and the laser-cut pieces were designed in Inkscape.


The inner structure of the Fab Speakers.


Early prototype with cardboard frame and a milled circuit board.

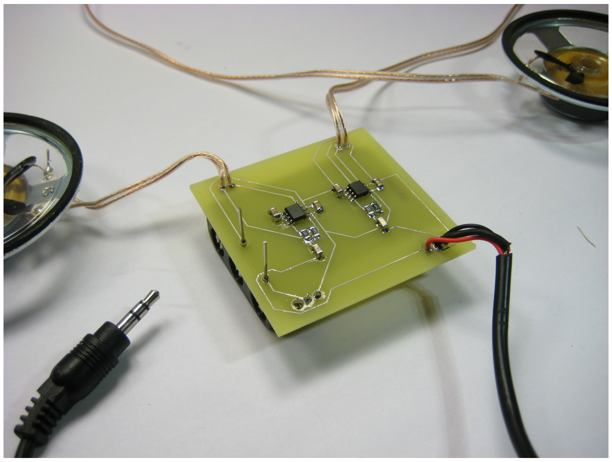
Design and Prototyping

For the speakers, as with the Fab FM, overall functional definition and, in particular, component selection was crucial to setting requirements for the electronics and the enclosure. In this case, the choice of the power source (three AAA batteries) narrowed the selection of potential amplifier circuits and provided an overall constraint on the size and form of the speaker housing. The size and power characteristics of the speaker elements also helped determine the electrical and structural design. Again, initial design and prototyping of the circuit board and enclosure proceeded more-or-less in parallel, although this time I was doing both myself.

The circuit design was primarily determined by the choice of amplifier chip. I wanted something that could be powered at 4.5 volts, that had coarse enough pitch (distance between adjacent legs) to be easily soldered, and that seemed likely to continue to be produced. I selected the TPA301D / TPA701D (two compatible chips) and designed the rest of the circuit based on the suggested application note in its datasheet. An initial milled circuit board confirmed the functionality of the design and its compatibility with the power supply and speaker element. Its size was mostly determined by the battery holder, as the other components were much smaller or, in the case of the speaker elements, not mounted directly to the board.

Through a series of sketches, I settled on the basic cylindrical shape with upward-facing speakers and batteries coming out the bottom. To test various possible arrangements of the plywood, fabric, and veneer, I simulated them using laser cut cardboard and paper – materials that are cheaper and easier to cut. Strict adherence to the structure of the Fab FM would have involved trapping the speaker element between fabric and a ring of veneer, with another piece of fabric wrapped around sides of the speakers. This arrangement, however, had a number of drawbacks: it would have made inefficient use of a (relatively-expensive) sheet of veneer; it would have involved lining up and gluing two pieces of fabric under a thin piece of veneer; it would have required a seam to join the fabric; and it would have meant enclosing the speakers with a soft material, minimizing their resonance. As a result, I decided to wrap the entire top face of the speakers with fabric, and surround the sides with a veneer strip. The height of the speakers was determined by the width of available veneer strips, meaning that they could be cut to length with scissors rather than laser-cut. To prototype this arrangement, I laser-cut and assembled the plywood frame, taped the fabric and veneer in place, and took a photo that captured the resulting appearance. Initially the fabric covered only the top face of the speakers, but this made the diameters of the top and bottom different so the veneer didn't attach well. I tried to adjust the diameters for the exact thickness of the fabric, but worried that this would limit the flexibility. Instead, I kept the diameters the same and added a second piece of fabric around the bottom face to keep its diameter the same as the top.

Confident that the circuit board would fit within the general parameters of the design for the speaker housing, I ordered a batch of PCBs from Advanced Circuits. These barebones boards have no solder-mask (the typically-green coating of the board's copper) or silkscreen (lettering) but ship the next day and were relatively cheap (around $8.50 each in quantity 12). They were almost identical to the initial milled board. Once the circuit boards arrived, I continued to refine the design for the laser-cut frame. Rotating the struts by 90 degrees allowed them to hold up the speaker elements. Moving the holes for the cables to the outside of the bottom face meant that they could be soldered to the circuit board without threading them through the enclosure - allowing the entire circuit to be tested before beginning assembly of the housing. Switching from four struts to three meant that the entire plywood frame fit inside the smallest material size offered by online laser-cutting service Ponoko. It also allowed the struts to hold the circuit board in place, eliminating the need for hot glue (which might have worn out over time). I also created a wall-mounted variation of the speakers that combines both speaker elements into a single frame. This version uses the same circuit board, with a 5V wall power supply soldered in place of the battery holder. I eventually ordered a second batch of circuit boards, but these were basically identical to the first aside from the addition of holes in the corners (to make it possible to screw the board down if desired in a variation).


Speaker circuit and electronics.


Wall-mounted variation of the speakers.

Workshop

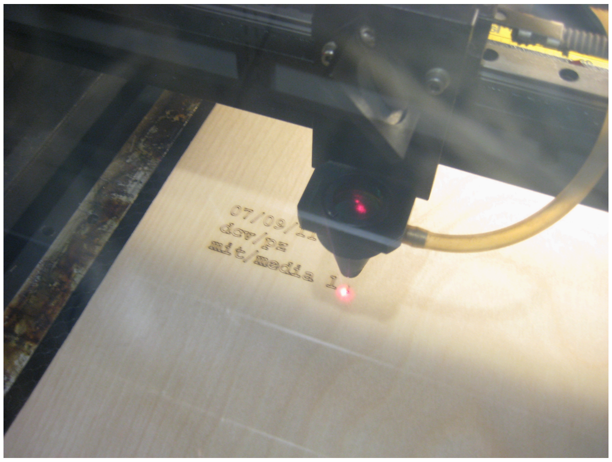
My first experience with someone other than me assembling the speakers was when I brought them to the FabLab at the South End Technology Center in Boston. There, a group of high-school and middle-school students work as facilitators during the hours on Thursday evening when the lab is open to the public. I came on a Tuesday, during the hours when the students would develop their own skills and projects, accompanied by a friend who visited regularly. There were four students present, one of whom was working on his own electronics project (modding an XBox). When I showed the students they assembled speakers, they were excited about the possibility of making them for themselves and the other three students started to solder together the circuit. The next week, I returned alone with the remainder of the materials and we completed and tested the circuits. We then laser-cut the plywood parts, which took longer than expected because of difficulties with the machine. In the end, we cut parts for two of the students, one of who finished assembling the speakers on her own. This initial experience made me confident that the speakers could be assembled by people without extensive experience with electronics or the soldering of surface-mount components.

Later, I organized a workshop to more thoroughly test the personalization and construction of the speakers by a general audience. In an attempt to recruit a diverse audience, I advertised the workshop only with physical fliers, placed in a variety of coffee shops and other stores in Cambridge. They were headlined "Make your own speakers!" and included a picture of the speakers and the following text:

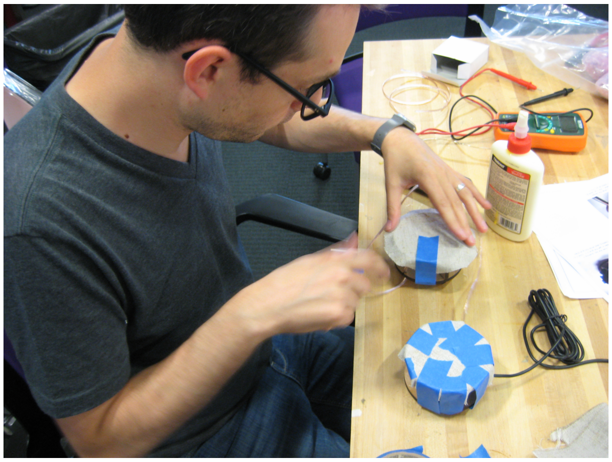
"In this free workshop, you'll learn to solder and use a laser cutter in the course of making your own set of portable, battery powered speakers (compatible with any device with a standard audio jack).

"No prior experience with electronics or laser cutting necessary, but general craftiness is a plus!"

Seven participants attended the workshop, which was held in the High-Low Tech lab space on a Saturday, starting at 10 am and scheduled to finish at 5 pm. Participants completed a questionnaire at the start and end of the workshop, which asked about their background, experience, and opinions of electronics and laser cutting. All seven completed both surveys, although one participant who arrived late did them both at the end. The participants had a mixture of experience with art or craft (these were grouped in a single question), design, and computer programming but little with electronics and almost none with the laser-cutter. Specifically, of the participants, four reported either a lot of experience or being an expert / professional with design, art, or craft. Four reported either a lot of experience or being an expert / professional with computer programming, including two of the previous four. For electronics, one participant reported a lot of experience, two some experience, and four a little experience. One participant had a little experience with laser-cutting (ordering parts from Ponoko) and the rest none. The participants ranged in age from 25 to 35, all were white, one female and six male.



Laser-cutting personalized plywood parts.

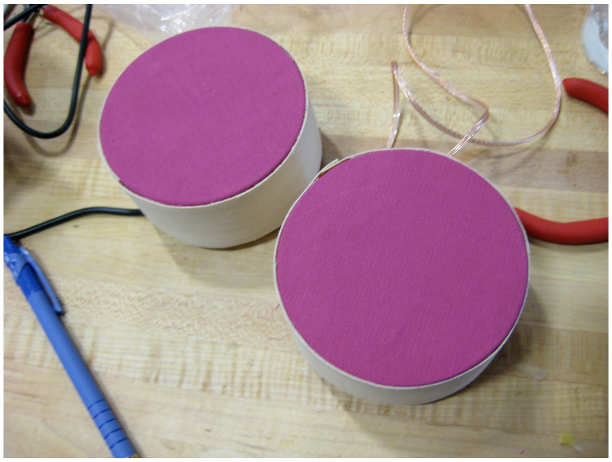


Gluing fabric onto the speakers.

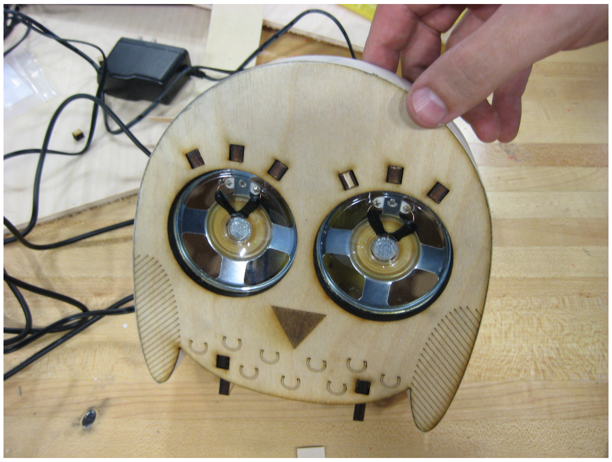
After completion of the initial questionnaire, I distributed a booklet of assembly instructions for the speakers to each participant and used them to introduce the workshop. Participants had the choice of making either the original two-part tabletop speakers or the integrated wall-mounted unit. The process was divided into three main stages: soldering the electronics, laser-cutting the plywood, and assembling the speakers. As most of the participants reported experience with soldering but not surface-mount components, I began with a demonstration of the technique, using tweezers to position the components. Each participant received a bag with the circuit board and surface-mount components and soldered these together according to a diagram in the booklet. For the most part, this proceeded smoothly, with participants able to correctly solder the circuit. I had to help a few desolder incorrectly-positioned components or to get a sense of what a good solder joint looked like. Some of the circuits didn't work at first, with one of the two speaker elements either silent or making a repeated clicking noise, but these problems were easily fixed by inspection of the circuits for missing or incorrectly soldered components.

After lunch, I briefly introduced the laser cutter and its control software. The design files for both speaker variants were on the laser-cutter computer and participants had the opportunity to personalize them before sending them to the machine. Participants operated the laser-cutter themselves with my supervision. After cutting out the plywood parts, participants assembled the speakers using their own selection of fabric from our research group's stock. This part of the workshop required little support from me aside from a few suggestions on the best way to iron on the veneer strips. One participant chose to house the speakers only in the plywood frame, omitting the fabric and veneer. As a result, he finished and left early. The other participants finished around 4:30 pm.

Four of the participants built the tabletop pair of speakers, two made the wall-mounted ones, and one designed his own custom enclosure (pictured below). Another participant wanted to build a custom enclosure using a cigar box he brought the workshop. He designed a mounting system for the speaker elements and circuit board on paper, but wasn't able to transfer the design to a CAD software (Inkscape or Corel Draw). In the end, he made the wall-mounted speaker unit. One of the participants assembled the tabletop speakers, but using a wall-power supply instead of batteries. All six of the participants that made one of the provided designs personalized the speakers by engraving their name or initials on the bottom.



Personalizing speakers through the selection of fabric.



An owl-like variation of the speakers, created by a workshop participant.

On the post-workshop survey, participants expressed satisfaction with the workshop and an interest in continuing to learn more about its topics. All seven reported completing a project they were happy with during the workshop. When asked their opinion of the workshop overall, six selected "I loved it" (the highest option on a five-point rating scale) and the seventh chose "I liked it" (the next highest option), giving an average score of 4.86 of 5. Of the individual workshop portions, electronics was rated the highest (average of 4.71), followed by laser cutting (average of 4.43), and then craft (average of 4.29). Six reported that the overall pace of the workshop was "about right", while one selected "somewhat too hard". All seven selected "about right" for the overall pace and length of the workshop. On a seven point scale, five participants selected "strongly agree" (the highest option) when asked if they were interested in taking another workshop like this one; the other two selected "agree" (the next option). Four selected "strongly agree" when asked if they had learned new skills in the workshop; two selected "agree"; one "somewhat agree".

Overall, the workshop demonstrates that people with no experience with laser-cutting and little with electronics can assemble their own device, given the right scaffolding. The soldering of surface-mount components, typically considered harder for beginners, was within the abilities of the participants. Everyone soldered their own board together, although they sometimes require assistance to fix mistakes (e.g. desoldering components that were in the wrong orientation). The laser-cutting and assembly didn't present any serious difficulties, although design of new forms could be challenging for people without experience.

That one of the participants was able to design and build a custom variation on the speakers within the workshop shows that the provided files are also of value to more-skilled individuals. It also suggests a possible relationship between them and those with less experience: by creating a new design for themselves, the former also generate a new template for others to use. For example, in the next workshop, I could offer the owl speakers as one of the variations for participants to construct. This is a simple but suggestive example of the way that open-source hardware can lead to increased diversity in the design of products.

Dissemination

One possible model for dissemination of the Fab Speakers is as a kit of electronic circuit board, components, and laser cut parts – similar to that proposed for the Fab FM. Additionally, however, the elements of the speakers have been designed to facilitate purchase in single units or small quantities from existing stores and services (i.e. without any custom offerings for the speakers). In particular, the plywood frame fits within the smallest material size offered by Ponoko (approximately seven inches square) and is the only piece that requires laser cutting. The circuit board could be ordered from a service like BatchPCB, which offers individual PCBs at a price comparable to that charged per-unit for larger quantities from other services (although with a longer lead time). The electronic components are available from a single distributor (Digi-Key). The veneer strips are available at most wood-working stores. Access to a good soldering iron (needed for the small surface-mount components) would be the biggest barrier to home assembly.

Ordering different elements of a product from different sources is certainly less convenient than buying it – as a finished product or a kit – from a single company. This is partly alleviated, however, by the ability for anyone to create public-facing product listings on the three sites mentioned (Ponoko, BatchPCB, and Digi-Key). This would allow someone to order the three main portions of the speakers by ordering products pre-defined by me. This doesn't require any explicit discussion or negotiation with the service provider, making it possible for anyone to offer their own customized version of the speakers for sale on the sites. It also allows the designer and creator of the product listing to profit when someone orders a product from their design. Finally, users desiring their own custom or personalized design could modify the design files for themselves and order them from the services for the same cost (or less) as one offered by someone else. This probably yield a total price of about $60 for the kit, although this would be cut substantially given direct access to a laser cutter rather than ordering parts from Ponoko.

Case Study #3: 3D-Printed Mouse

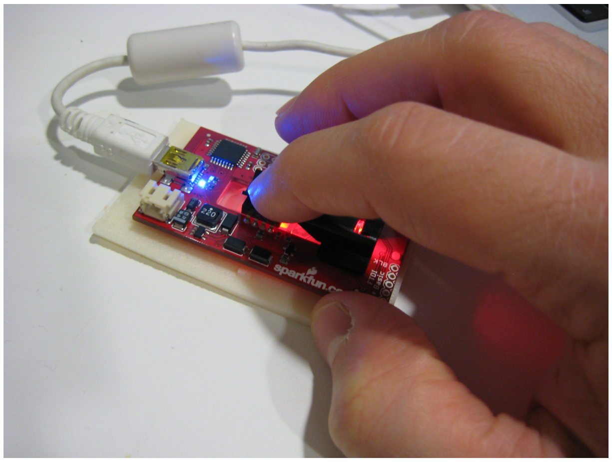
This case study explores the possibilities for making the enclosure of a standard computer mouse using 3D printing. The shift from 2D to 3D in the software design tools and fabricated parts greatly changes the process and outcomes for the construction and customization of a consumer electronic product. The individual parts become more complex, easing the assembly process but increasing the skills required to design them. Prototyping the mouse enclosures revealed possibilities for and limitations of creating functional moving elements within a single 3D printed object. The workshop explored the ability and outcomes of customization by skilled 3D modelers working with a standard, pre-supplied circuit board. This suggests a dissemination method: circuit boards produced in medium or large volumes combined with custom 3D printed enclosures.

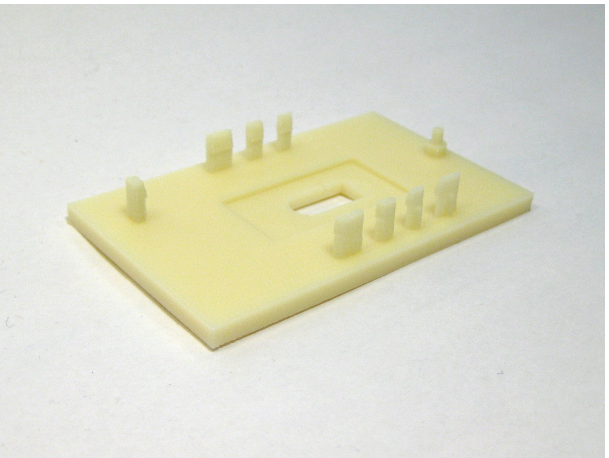
Construction

The mouse consists of a circuit board enclosed within two 3D-printed parts (base and shell) along with a purchased plastic lens. An ADNS-2620 chip mounted on the circuit board does most of the work. It contains a imaging sensor and processes the recorded images to determine its motion across a surface. Three screws hold the circuit board against the 3D-printed base, trapping the lens in-between. All are designed so that the imaging sensor in the bottom of the ADNS-2620 is held at the correct position relative to the lens and the surface beneath the mouse. Only the outer rim of the base plate touches the surface below, reducing friction. The curved shell covering the top of the mouse connects to the base plate with four screws. Its walls are between 1 and 2 mm thick, reinforced with a pair of crossing ribs. The shell has two flexible flaps, oriented so that depressing them clicks buttons mounted on the circuit board. An ATmega328p microcontroller, running a slightly-modified version of example code from SparkFun, communicates with the ADNS-2620 and over a USB cable to the computer.

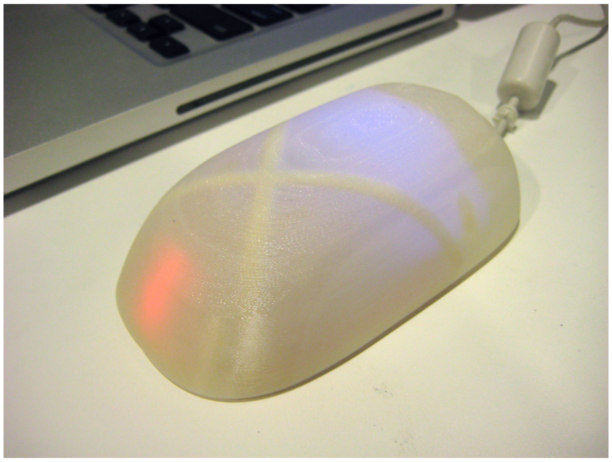
Design and Prototyping

As in the first two case studies, component selection was critical to guiding the design of the circuit and enclosure. The ADNS-2620 was selected for a few reasons: it was cheap and available in small quantities, it's part of a family of related parts (suggesting continuing support), and SparkFun sells a breakout board for it. Additionally, the chip and supporting components (lens and LED clip) are well-documented, including both electrical and mechanical properties and 3D reference models. For designing the 3D models, I used the Rhino software, which was recommended to me for its flexibility in the kinds of shapes it can create. The prototyping process also served as my introduction to 3D modeling and to Rhino. The parts were mostly printed on a Stratasys Dimension Elite housed at the Media Lab, but I also tested the in-house Invision machine and SLS-printed nylon ("white, strong, and flexible") parts from Shapeways.

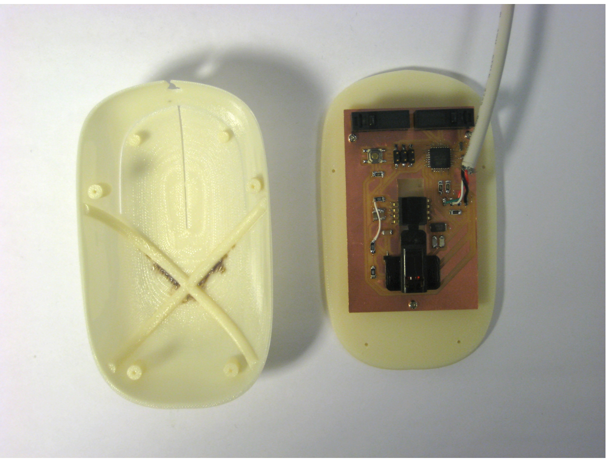

Initial 3D-printed baseplate prototype with SparkFun ADNS-2620 breakout board.


Baseplate prototype printed on the Stratasys Dimension. The hooks broke off when the circuit board was inserted.

My first prototypes consisted of 3D printed parts designed to mate with the SparkFun breakout board. They served as a way to verify the alignment and mounting of the lens, circuit board, ADNS chip, and the base plate. The original idea was to snap fit the circuit board in place with cantilevered hooks. This proved infeasible with the rapid prototyping machines available at the Media Lab. When the circuit board was inserted into parts printed on both the Dimension and the Invision, the cantilevered hooks broke. Later tests with an SLS-printed nylon part from Shapeways proved successful, but the advantages of snap-fit were questionable and I wanted to continue to use the in-house machines. As a result, I tested screwing into parts printed by the Dimension; this worked well. An M1.6 screw with an outer diameter (including threading) of 1.6 mm, and length of 6 mm held tightly in with holes of diameter 1.2mm through 1.5mm, even when removed and re-inserted an additional time.



Button-less prototype with SparkFun breakout board and parts printed on the Dimension.



The first prototype with buttons, consisting of a milled circuit board and Dimension-printed parts.

I then designed a complete enclosure for the SparkFun breakout board, including both an updated baseplate and a new shell. These were printed on the Dimension. Screws attached both the shell and the circuit board (with lens beneath) to the baseplate. This yielded a functional but button-less mouse. To add buttons, I designed a custom circuit board, adapting the Eagle CAD files provided by SparkFun for their ADNS breakout. Specifically, I extended the circuit board to include buttons, added two additional screw holes, modified the board for use with slightly larger parts for easier manual soldering, and replaced the Mini-USB jack with holes for direct soldering of a cut USB cable. To be able to click the buttons, I sliced through the 3D model of the shell to create flexible flaps with posts positioned just above the button's plunger. This yielded a prototype with working buttons. A subsequent iteration of the circuit board rotated the buttons 180 degrees (moving their plungers from the board's edges to its middle) and separated them slightly to make room for the USB cable to go between them. The posts on the shell's flaps were moved to align with the positions of the button plungers and the slices that define the flaps were thickened slightly to ensure freedom of movement. These updated designs yielded another prototype with milled circuit board and parts printed on the Dimension.

Workshop

The workshop was an investigation of the ways in which skilled 3D modelers could customize the design for the 3D-printed parts of the mouse while retaining the same basic circuit design and layout. In preparation for the workshop, I ordered approximately 15 circuit boards, from Golden Phoenix. They cost approximately $120 and arrived in about two weeks. These boards were similar to the last milled prototype but added mount points for two analog sensors, to provide the option to replace the buttons with some other sensor. I also ordered the electronics and other components (e.g. lens and LED clip) needed to assemble a mouse from these circuit boards.

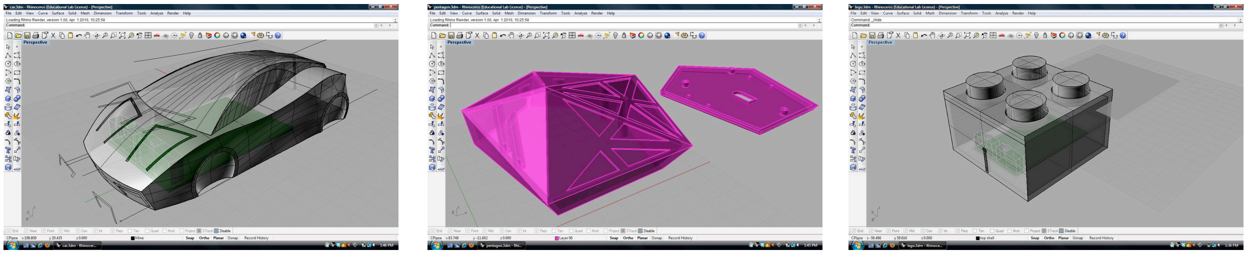
I recruited participants through emails to individuals and groups with experience with 3D modeling, e.g. students from the MIT class How to Make (Almost) Anything and from the Harvard Graduate School of Design. The email specifically requested participants with a knowledge of Rhino (and a working copy on their own computers) and promised a free 3D printed mouse in exchange for participation. Eight people attended, one accompanied by her boyfriend. The participants ranged in age from 21 to 31; five were men, three women; four Asian and four white. Six reported regular or expert / professional experience with architecture, a seventh reported expert / professional experience with product or industrial design. Three ranked themselves as experts or professionals at 3D modeling, three said they do it regularly, and two reported some experience. In general, they reported little experience with electronics.

The workshop began with a presentation on the possibilities for integrating digital fabrication with electronics, including motivation and examples of existing products as well as the previous case studies. Participants were encouraged to think of customizations along a number of axes, including form, texture, and materials. They were told that the buttons could be mounted off the circuit board (and connected to it with wires) or replaced with some other sensor (either digital or analog). Because the emphasis was on the modeling of the mouse enclosure, participants were told the circuit boards would be soldered for them or that they could come back another time to do it themselves. Additionally, I offered to mill a custom circuit board if required for a particular design. The plan was to print participants' 3D models in the week or so following the workshop and then have them come back to pick up and assemble their mice.

After the initial presentation, participants were asked to spend ten minutes or so sketching ideas for their mouse and present them to each other. The remainder of the workshop (approximately four hours) was spent 3D modeling with Rhino. Participants were given the 3D model for my latest version of the mouse. This included a rough model of the circuit board showing its overall dimensions, the location of the screw holes, and the position of the plungers on the buttons. It also provided references for structural elements like the opening for the lens in the baseplate and the screw posts and holes.

Of the eight participants, only one pursued a design involving additional materials beyond the electronics and 3D printed parts found in the prototype. His mouse was intended to strap to its user's hand and provide pressure sensors on the fingers in place of buttons. Another participant planned to mount the buttons off the circuit board in order to allow an alternative grip while using the mouse. A third participant required slight modifications to the shape of the circuit board to fit it within his enclosure, although this didn't require any changes to the positioning of the electronic components themselves. The other five participants planned to use the default circuit board and components. Two of the participants emphasized the light generated by the circuit (which allows the optical sensor to see the surface beneath) by creating an interior pattern or texture on the 3D printed shell. When the LED is illuminated, it shines through the translucent 3D printed parts, revealing this pattern.

Only two participants completed their models within the time of the workshop, but three more later emailed them to me. Two other participants created 3D models that gave a fairly complete sense of the desired form for their mice but which were not closed solid models suitable for printing. The last participant, who had only some 3D modeling experience and chose a complex form for his mouse, did not make much progress. I had four of the five completed models printed on the Dimension printer at the Media Lab. The fifth, although seemingly correct, crashed the 3D printer's software. Printing typically required about 5 to 6 hours of machine time, followed by immersion in a solvent bath for the dissolving of support material, yielding a typical total of 24 hours or more between completion of the 3D model and availability of the printed parts.



Screenshots of 3D models designed by workshop participants.

Assembly of the mice from the printed enclosure was carried out to varying levels of completion. The mouse with straps was assembled and functional, but we didn't find an approach that allowed completion of the pressure sensor within the participant's available time. One participant picked up his enclosure and circuit board, but I'm not sure if he put it together. The third printed enclosure was the one that required a custom circuit board, and we were unable to assemble a working circuit before the participants left the country. The fourth printed enclosure awaits the soldering together of a working circuit board. Two of the printed enclosures required sanding before the baseplate and shell would fit together. In both cases, the 3D models of the parts could be positioned in the desired final orientation without intersecting, but overhangs on the opening of the shell prevented the baseplate from sliding into place.


Mouse variation with internal texture.


Mouse variation that straps onto user's hand.

Assembly of the circuit boards for the mice of the workshop participants proved to be unexpectedly time-consuming and difficult. In particular, the small size of the resonator connected to the microcontroller made it hard to solder correctly. The number and diversity of parts on the circuit board makes it slow to assemble and harder to parallelize. Milling an custom circuit board is also relatively slow (approximately 1-2 hours for a board of this size). Additionally, during the workshop, I discovered a flaw in the circuit that made the mice incompatible with some Windows PCs. (I had previously tested only on Macs.) This required the addition of two zener diodes to clamp the voltage on the USB data lines to 3.3V as required by the standard (as opposed to the 5V used in my initial prototypes).

The workshop offers lessons for the process of designing an electronic product with a 3D printed enclosure. First, it suggests that the enclosure can be designed by those with little experience with electronics, provided they have an existing circuit to work with. Second, it calls into question the relevance of incorporating custom materials or modifications to the circuit board for a particular mouse design. Perhaps because of the extended period between completion of the 3D model and availability of the printed parts, participants seemed mostly uninterested in designs that would have required additional post-fabrication work. This may have been partly a consequence of the workshop structure, which dedicated time only to modeling not assembly, but, in general, the delay between modeling and assembly poses a barrier to iteration. Without being able to quickly test the combination of the digital design and physical materials, it's much harder to integrate the two. Third, the workshop suggests the diversity of forms possible for enclosing a standard circuit board and, therefore, the decreased importance of being able to modify or customize the board itself. The flexibility of 3D printing makes it likely that you can fit the electronics into a design, given basic constraints on size and orientation.

Dissemination

The mouse seems amenable to different methods of dissemination than the radio and speakers. In particular, because assembly of the 3D-printed enclosure requires little effort, it's unclear if it makes sense to accompany it with a circuit board that requires manual assembly by the end-user. This suggests a model in which the circuit board is sold already assembled (requiring higher-volume production to achieve the necessary economies of scale) accompanied by on-demand 3D-printing of custom cases. For example, a slight modification of the existing SparkFun ADNS2620 breakout board (to add buttons) would allow it to serve as the circuit for a variety of enclosures (like those produced in the workshop). The current board costs \$30; adding buttons might increase this to \$35 or so. Ordering the 3D printed parts from Shapeways is approximately \$45, giving a total of around \$80 for a complete mouse. Because of the specialized skills required for 3D modeling, this dissemination process suggests a separation between the designers who would produce custom variations and the individual customers who would buy them.

5. Lessons Learned

This chapter derives some practical lessons from the design, production, and customization of the case studies. It starts with a discussion of the integration between electronics and enclosure – because the process of aligning the two has important implications for the design of each and should occur early and throughout the prototyping process. It then discusses the three main processes used in the thesis (electronics, laser-cutting, and 3D printing), providing lessons and advice for each. Throughout, implications are drawn for software design tools and the sharing of digital design files as open-source hardware.

Integration of Electronics and Enclosure Throughout the Design and Prototyping Process

One important lesson brought out by the case studies is the importance of selecting electronic components early in the process. This choice is determined by both functional and aesthetic requirements and it's important to test both before committing to particular components. Their selection, in turn, is essential to shaping the precise design of both the circuit and the enclosure. The resulting constraints fall into a few main categories.

Size. The components have to fit within and, thus, help determine the minimum size of the device (e.g. the speaker elements in the speakers). They also play a role in the overall aesthetics of the form (e.g. the shape of front face of the Fab FM).

Orientation. The desired placement of the components help to determine the overall construction of the device, including the relative arrangements of the circuit board and structural materials. For example, the horizontally-mounted potentiometers on the radio's circuit board meant it had to be oriented perpendicularly to the front face. The need to access the speaker's batteries led to their alignment (and that of the circuit board) with the bottom face of the speakers.

Construction. Its role in holding the electronic components in place constrains the arrangement and composition of the enclosure. For example, the combination of plywood, fabric, and veneer in the radio was partially determined by a need to secure the speaker. The baseplate of the mouse was designed to trap the lens in place between it and the circuit board.

Openings. Some components need to penetrate the enclosure, which has other functional implications. For example, holes in the radio and speakers affect the quality of the sound they emit. The mouse needs to be assembled around the USB cable.

Power. The choice between a power jack (radio), removable batteries (speakers), wired supply (mouse), or other power source affects many of the preceding characteristics as well as placing requirements on the design of the circuit itself.

Once the main components have been selected, design of the circuit and enclosure can proceed in parallel, respecting the resulting constraints. During the prototyping of the case studies, my access to digital fabrication machines allowed for quick testing and iteration. The laser cutter, in particular, lets you try a new or altered design in a few minutes, making it possible to rapidly refine the structure. Both circuit board production and 3D printing have longer turn-around times, even given direct access to the relevant fabrication machine. As a result, during the construction of the radio and speakers, the enclosure underwent many iterations for each revision of the circuit board while, with the mouse, the circuit and enclosure tended to iterate together. The quicker iteration allowed by the laser cutter seems to help not only in decreasing the time to a finished design but also in encouraging more experimentation and rethinking of the overall construction.

Once compatible designs have been generated for the circuit and the enclosure, it's easy to make some changes to one of the two without affecting the other (or the integration of the two). For example, as long as the power supply remained the same, the speaker's amplification circuit and chips could be changed without affecting its structure. Similarly for the digital FM tuning module at the core of the radio. The shape and appearance of the enclosure can change as long as it retains the same orientation and dimensions with respect to the electronic components.

Implications for Open-Source Hardware and Software Design Tools

The digital files for the circuit and its enclosure capture much of the effort and creativity that was expended in their design. It makes it possible to change either of the two with the confidence that it will still work with the other (e.g. that components will line up with their openings or that the circuit will fit inside the enclosure). This means that modifications and improvements to the design of the product can also be captured within its digital files, which can be shared, studied, and modified online. This is the core of the way in which digital fabrication enables the application of the principles and practices of open-source software to the development of hardware.

The practical difficulties of integrating the electronics and the enclosure suggests the importance of design tools which are aware of both these aspects of a device. Being able to reference the geometry of the electronic circuit and components when designing the case – and vice-versa – would greatly facilitate the design of both. It's possible to do this manually with existing tools, but programmatic support would keep this correspondence up-to-date and exact. Of course, there are complications in providing such software support. Low-cost circuit design tools tend to work only with the 2D geometry of components (i.e. their footprint on the PCB itself) rather than the 3D geometry needed for alignment with enclosures. Further, with laser-cut enclosures, the design file may not represent the 3D geometry of the assembled enclosure but only the flat shapes of the individual parts. Still, it seems feasible and valuable for tools to provide additional support for the integration of the circuit and case of a device.

Electronics

The fabrication of electronic circuits has an established history both in industry and among hobbyists. This section therefore shares some of my learnings and conclusions from the case studies without claiming to offer particularly unique or novel contributions. In particular, my focus on small-scale production required strategies that minimized manual labor on the part of the individual product designer without requiring large capital investment. I also draw some conclusions about the ways in which the electronic elements of a product can be designed to facilitate customization.

The case studies involved a number of different techniques for prototyping and producing circuits, each with its own unique advantages and limitations. The design and fabrication of a custom circuit board saves significant time compared with hand-wiring of components of components on a breadboard or prototyping board – perhaps even in quantities of one, but certainly in volumes of 10 or more. Milling a circuit board is therefore both a way of creating a single board with specific dimensions and layout, but also provides a convenient method for testing a circuit design before ordering it from a fabrication service. Given access to a milling machine, production of a circuit board is both relatively quick (usually an hour or two) and cheap (typically less than a dollar of copper-clad stock). All of the boards I milled for the case studies were single-sided, but this wasn't a serious obstacle – it just required an occasional jumper wire. The size of the milling machine's tools also places a minimum size on the pitch of the components used but, again, this wasn't a problem because I already had an interest in using larger-pitch components to ease the soldering process.

While access to a milling machine can lower the cost and turn-around time for prototyping a circuit board, online fabrication services offer an accessible alternative. Some services offer a fixed price for a panel, usually tens of boards, which is convenient for small-scale production. For prototyping of smaller quantities, various services will distribute a panel among various individuals, which usually places stricter constraints on the characteristics of the individual boards. For example, some of the services used for the case studies offer small volume runs but without solder mask or silk-screen; others take longer to distribute a panel's board among its various customers. In general, though, it was possible for me to find a reasonably-priced service that satisfied my time and specification requirements.

Procurement of electronic components is in some ways easier and other ways harder than that of circuit boards. It's easier in the sense that you can simply order components from online distributors much like you'd buy a product from any online store. Individual prices tend to be low and parts arrive quickly, with familiar shipping options. The difficulty comes in ensuring that the desired parts remain available. Electronic components, particularly the more complex or high-tech ones, are updated and replaced frequently and it's easy to end up with a circuit designed for parts that are no longer sold. Usually alternatives exist, but they may require significant modification to the circuit design or layout. Circuit boards may have longer turn-around times than components, but, in general, you can always order the board you need. Therefore, when doing a small production run of an electronic devices, it's often wise to order the components first, then the circuit boards (assuming the circuit has already been tested with the relevant components).

There are a variety of processes and options for assembly of the circuits. Surface-mount components are relatively amenable to small-scale automation with inexpensive ovens, although this wasn't explored in the case studies. Through-hole components work well for kit production (i.e assembly by the end user), as they can be soldered with inexpensive soldering irons and are relatively robust to clumsiness or rework. Some types of connections are particularly time-consuming to solder. For example, attaching the USB cable to the mouse circuit board required manual stripping of four small wires and individually soldering them to the PCB. Mounting the potentiometers on the Fab FM circuit board and the buttons on the mouse required careful attention to ensure that they were perpendicular to the PCB. When planning for small-volume production, some up-front work (e.g. building jigs for aligning components, or redesigning the PCB to use easier to solder components) may save time over the course of the production run.

Implications for Open-Source Hardware and Software Design Tools

One lesson that stands out from the workshops is the unlikeliness of creating a custom circuit board within the context of building a custom variation of an electronic product. In the Fab FM workshop, many of the participants had experience in PCB design and milling, but few attempted to create their own circuit board or incorporate different or additional components in their designs. In the mouse workshop, few of the participants seemed interested in customizing the shape of the board or the inputs to it. This suggests that open-source processes in the design of a circuit board require a longer time frame than a one-day workshop. It also implies that to support customization of the electronics in the course of building the device, it's important to design flexibility into the provided circuit board itself. For example, the ability to substitute a wall power supply for the batteries of the speakers facilitated its transformation into a wall-mounted unit. Breaking out additional inputs to the microcontroller in the mouse allowed the participant who was interested to substitute pressure sensors for the buttons. Flexibility in inputs, outputs, connectors, cables, mounting schemes, etc. can all allow for modification of the electronics without a need to design and fabricate a custom circuit board.

One specific software function that would benefit the development of open-source electronic hardware is the ability to isolate and track changes to the design of a circuit. For example, I'd like to be able to send SparkFun a file representing the addition of buttons to their ADNS breakout board. In general, this ability to incorporate specific changes made by others into a circuit would greatly facilitate open-source collaboration in electronics.

Laser Cutter

The use of the laser cutter in the case studies emphasizes the assembly of a 3D structure from flat pieces of multiple materials. It takes on some of the hand-crafted associations of materials like wood and fabric while retaining the precision and reproducibility of digital design and fabrication. This combination yields a process which allows customization in both the digital and physical realms without requiring extensive skill or expertise in either. It gave the workshop participants an opportunity to mix high-tech skills with hands-on activity and allows people from either a craft or a design background an entry into the other.

In designing for the laser cutter, the fundamental consideration is the nature of the assembly. The radio and speakers both used a similar construction: two parallel plywood faces connected by press-fit struts, then covered in fabric and veneer. This structure is implied by the shape of the parts in the digital design file but is not explicitly modeled in the 2D software CAD tool. As a result, it's easy to customize the design but only while retaining the basic assembly technique. With both the radio and the speakers, workshop participants modified the shape of and engraving on the faces while keeping the existing strut and hole structure and dimensions.

The case studies revealed some of the ways in which these laser-cut assemblies can be designed to accommodate variation in material choice or characteristics. The thickness of plywood often varies from sheet to sheet, even if the nominal dimensions are the same. For this reason, it's helpful to leave extra room along the corresponding dimension of a hole intended to accept a plywood part. In designing the radio and speakers, I adjusted the tightness of the press-fit using the other dimension of the holes (i.e. the one that corresponds to the width of the strut not the thickness of the plywood). Differences on the order of tenths of millimeters can mean the difference between a loose and tight fit. Once the dimension is tuned, someone can use it within a new shape or design and know that the pieces will fit together properly, which dramatically reduces the need for iteration. (For example, the owl speakers only needed to be cut out once.) The precise dimension for a tight press-fit does, however, depend on the specific laser-cutter used.

Different fabrics also have different thicknesses, and so the designs of the radio and speakers aren't dependent on a precise dimension. Instead, they're assembled so that matching layers of the fabric are used when equal thicknesses are required (e.g. wrapping fabric around both the top and bottom face of the speakers to yield the same diameter for each). Changing the fabric of the radio and speakers was a simple but effective means of adjusting the overall look and feel of an individual product.

Implications for Open-Source Hardware and Software Design Tools

While 2D design files for laser-cut parts are easier to modify than 3D models, they don't capture as much of the final form. This means that open-sourcing the design of a laser-cut product requires additional information about the materials and assembly process. Still, much of the essential aspects of a design are captured in the file itself: e.g. the relative positioning and sizing of press-fit holes, the orientation and dimensions with respect to the electronics, and the overall set of pieces required.

The kinds of customizations seen in the workshops suggest possibilities for product-specific design tools. For example, a very simple interface could allow someone to enter a custom message to be engraved on the bottom of the speakers. A slightly more complex tool might allow for designing a custom engraved pattern for or the overall shape of the radio or speaker faces. More sophisticated tools could allow for 2D arrangement of the electronic components, yielding a custom design for both the circuit board and enclosure.

Looking beyond tools to support customization of existing designs, it’s possible to imagine software created specifically for designing laser-cut assemblies. For example, such a tool could support common assembly paradigms (like the two faces and perpendicular struts used in the radio and speakers), automatically generating the aspects of the geometry that they imply (e.g. maintaining a correspondence between struts and holes). It could also support parameterization based on thickness of the material to be cut and the tightness of press-fit desired. By building in the constraints of the fabrication process, this type of software would leave the user free to focus on the creative aspects of the design.

One particular problem that I encountered frequently in working with the laser cutter was file format incompatibilities between different software tools. In theory, DXF is supposed to provide a standard for 2D CAD files, but in practice it is interpreted in different ways by different programs. I used a mix of PDF, SVG, and old versions of the Adobe Illustrator format, but never found a combination of file formats and tools that consistently worked with the laser-cutter's software.

3D Printing

3D printing covers a diverse range of rapidly evolving processes and the case studies touch only on a few, and those only briefly. It's possible to draw some practical lessons from this experience, but these are likely to become obsolete as the technology advances. As a result, while this section gives some specific suggestions, it also attempts to raise more general questions about future possibilities for the integration of 3D printing into the production of consumer electronics.

In many ways the 3D printing as illustrated by the mouse prototypes is the opposite of the laser-cutting seen in the radio and speakers. It uses a minimal range of materials, emphasizes pre-fabrication design over post-fabrication craft, provides less direct access, and requires specialized skills in 3D modeling. The enclosures designed by the workshop participants were almost completely specified by their digital representations, requiring only a few screws for final post-fabrication assembly. The nature of these parts, combined with the expense and relatively slow turn-around times of the 3D printers (e.g. compared to a laser cutter) de-emphasized manual skill, post-fabrication customization, and iteration. It places the emphasis instead on digital skill and expression in 3D modeling.

The 3D printers used for the mouse prototypes allow for vast freedom in the shapes and forms of the fabricated parts. This allows for a range of physical functions from a single material. In the mouse prototypes, the ABS plastic of the Dimension serves for precise alignment of components (e.g. lens), for structural strength (ribs), for use as a hinge (button flaps), for light diffusion and patterning (textured surfaces), for sliding against another material (bottom rim), and for mounting screws. The printed parts also forms the overall shape and appearance of the mouse. The printers used for the mouse, however, allowed limited aesthetic flexibility; the resolution (slice thickness) of the Dimension is fairly course (0.007" compared to 0.001" for some machines) and the material used is a relatively unattractive yellowish off-white.

The functional and aesthetic possibilities for 3D printing are continuing to expand as the technology progresses. An increasing diversity of materials and possibilities for multi-material printing pose many important questions for the creation of consumer electronics. For example, in what ways will 3D-printed parts be able to match or surpass the visual and aesthetic qualities of those made with more traditional processes – and which qualities will remain dependent on mass manufacturing techniques? To what extent will multi-material printing provide a feasible substitute for assemblies of multiple parts from different materials? Will the lower tooling costs and volumes associated with 3D-printing make viable products whose markets are too small for traditional mass production? Will the flexibility of 3D printing be able to offer possibilities for customization that are attractive enough to offset increased production costs?

Exploration of the possibilities of cutting edge 3D-printing processes will continue to require access to the latest high-end machines. The expense of these machines places continuing importance on 3D-printing services, particularly for individual hobbyists or small businesses interested in creating or customizing their devices. These services make high-end rapid prototyping processes available for small orders but also constrain the ways in which individuals can work with them. Their long turn-around times (compared with direct access to a machine) make it more difficult to iterate a design or adapt it to variations in the electronics or other materials. Their margins make it harder for a small business to take advantage of economies of scale and place a limit on the extent to which they can reduce costs. While technological improvements will almost certainly enable faster and cheaper services, there's likely to remain a tension between use of the latest rapid prototyping processes and the ability to minimize production times and costs. Another interesting research question is the extent to which low-cost 3D printers will able to match the quality and flexibility of the more expensive models.

Implications for Open-Source Hardware and Software Design Tools

Compared with the other fabrication processes explored in the case studies, 3D printing emphasizes the pre-fabrication digital design process. With current software tools, this means that someone needs specialized skill in 3D modeling to design or customize the enclosure for a device, as seen in the mouse workshop. This virtualization of the making of unique or small-batch products, however, offers intriguing possibilities for open-source hardware and software design tools. It means, for example, that the digital file for a 3D-printed object contains almost everything needed to produce that object - no additional information or skill is required beyond access to the appropriate fabrication machine. This suggests that those models provide a basis for distributed sharing, collaboration, and customization of products.

In the mouse workshop, participants had difficulty ensuring that their models were printable, i.e. represented closed solid forms. Rhino is a surface-modeling tool, meaning that user is responsible for ensuring the edges of the surfaces align properly. Other tools, like SolidWorks, work with solid volumes, but their history of use with machining and molding make them more rigorous than is necessarily desirable for a flexible medium like 3D printing. This fabrication process suggests, rather, a hybrid paradigm, in which users can create freeform 3D surfaces with a thickness, something more akin to sculpting than either surface or solid geometries.

One important question not addressed by the mouse workshop is the extent to which open-source hardware or software design tools can help novices (those with little experience with 3D modeling) customize 3D designs. With the Rhino files for the mouse, for example, even small changes typically necessitate a moderate or higher level of skill with 3D modeling. This is in contrast to laser-cut designs, which can be personalized relatively easily by those without particular experience with illustration software. An interesting direction for future work, therefore, is the development of new examples and tools to facilitate customization by a diverse audience of varying skill and experience.

6. Modes of Production

This chapter presents the modes of production that digital fabrication enables for consumer electronic devices. These combinations of volumes of production, distributions of labor, and fabrication processes stem from reflection on the experience and lessons of the case studies.

One-Off Production

The case studies demonstrate some of the ways that digital fabrication enables the production of one-off consumer electronic devices. In particular, both the initial prototyping processes and the customizations performed in the workshops serve as examples of the creation of unique designs. The components and processes involved may get cheaper in larger volumes (particularly the electronics) but they are available in quantities of one and to individuals, without an initial negotiation or contract. It's possible to simply order the things you need (whether standard or fabricated parts) and assemble them into a one-off electronic device. In the case of products that already exist, this likely to be more expensive than simply buying a mass-produced one, but provides significant flexibility for the creation of a new kind of product or a variation of an existing one.

Designing a product from scratch, as Dana and I did with the Fab FM, takes a mix of skills: programming, electronics, PCB layout, industrial design, 2D CAD, etc. It may require intermediate prototypes to test functionality or aesthetics. Still, in the course of two weeks, we were able to create a finished, functional prototype of a new product with only tens of dollars in materials. Customizing an existing open-source design requires less specific or diverse expertise. An existing, working design can be selectively customized in the ways that someone cares about or is good at, leaving the rest unchanged. This can still lead to significant variation in the overall product, e.g. the owl speaker variation created by a workshop participant through the aesthetic (but not structural) modification of the laser-cut plywood parts.

The digital fabrication of the enclosure differs in some significant respects from a purely handcrafted approach. It can take advantage of the accuracy and precision of digital design to ensure alignment with the electronic circuit and components. It allows for iteration and refinement of form in software, which can take advantage of the reversibility and scriptability of that medium. It simplifies the skills and time required for physical assembly, while still allowing for craft and customization in that process. Finally, it facilitates sharing of designs as open-source hardware, so that one-off creations can become the basis for further reproduction or variation.

Artisanal Electronics

The manual assembly of laser-cut enclosures suggests two modes of production for consumer electronic products: artisanal (described here) and kit (discussed in the following section). By artisan, I mean an individual involved with all aspects of the production of a product, including its design, making, and sale. Artisanal processes also imply, in my definition, an ability to adjust the final product based on the qualities of the material inputs. The diversity of materials and rapid iteration characteristic of the laser cutter enable the application of these qualities to the creation of consumer electronic products. When working with variable materials like wood and fabric, there's value in individually adjusting the laser-cutting process according to the specific appearance or construction of a particular sample. On the other hand, digital fabrication can ensure the consistency of dimension and form need for compatibility with the electronic circuit and components. The lack of tooling means that although it's possible to make many copies of the same design, it's relatively quick and cheap to create a new variation of the design (e.g. to suit a new material). With prices of a few thousand dollars, laser cutters are already within reach of an individual or small business and likely to get cheaper in the future. They are fast enough to create tens or hundreds (perhaps thousands) of parts in a day, allowing for small-scale production in volumes large enough to suggest the possibility of making a living.

Artisanal production of enclosures for devices could be accompanied by a similar process for assembly of the electronics. The circuit board fabrication would likely be outsourced, but an individual could solder components onto tens or hundreds of circuit boards, particularly with surface-mounted components and some semi-automated tools (e.g. reflow ovens). At these scales, variation in the circuit is also possible – perhaps not for each individual device, but certainly in batches of tens or hundreds. This could take the form of a new circuit board design (e.g. to adjust for new versions of an electronic component) or of variation in the selection of components mounted to the board (e.g. to allow customization of the interface of a device). The similarity in the costs, quantities, and time required for assembly of an electronic circuit and of a laser-cut enclosure suggests they would provide a compatible workflow for an individual craftsman or small business and a similar balance of repeatability and customizability.

Kits

Another mode of production suggested by the laser cutter in one in which the customer assembles the product for themselves from a kit. As suggested for the Fab FM, this could take the form of a circuit board, electronic components, and laser-cut wooden parts to be soldered and glued together. By centralizing the digital fabrication processes (PCB production and laser-cutting), the kit means that the individual customer doesn't need access to the fabrication machines or the digital design files. By leaving the manual portions of the assembly to the customer, however, the kit frees its producer to concentrate on the more easily automated processes. The reproducibility of laser-cut parts would allow for the production of hundreds or thousands of kits but its lack of tooling means that each could potentially be individually customized by the customer on ordering the kit. Combined with individual involvement and customization in the construction of the device (e.g. in selection of fabric or other materials), kit production has the potential to create greater personal connection with consumer electronic devices.

Hybrid Mass/Custom Production

As demonstrated in the mouse case study and workshop, the flexibility of 3D printing allows both for simple post-fabrication assembly and for a wide variety of enclosures for a given circuit board. This suggests that 3D printing could be used to easily create a diverse collection of finished products around a standard, mass-manufactured circuit board - and the possibilities will continue to increase with improvements to 3D-printing technology. This goes beyond the selection from a fixed set of pre-defined choices offered by most current mass customization processes because it offers full control over the design of a custom enclosure. It still allows, however, for economies of scale in the production of the electronics, and the associated feasibility of the up-front engineering costs required for complex circuits. Open-sourcing of both the circuit board design and that of particular 3D-printed enclosures provides a template for the development of other cases, improving the speed with which they can be designed and the likelihood that they'll fit properly.

Given the specialized skills required to design or customize a 3D model, the combination of 3D-printed enclosure with a standard circuit board suggests the retaining of the traditional divide between manufacturer and designers on one side and the end customer on the other. It does, however, hint at some opportunities for changes to this relationship – for example, the manufacturer could open up their product listings for inclusion of enclosures by independent designers (similar to the marketplaces offered by Shapeways and Ponoko). Or the assembled circuit board could be made available as a component for incorporation into products offered for sale by the designer of the enclosure. By opening up the design and fabrication of a given product to customization by more designers, 3D printing has the potential to yield a greater diversity of consumer electronic products. Still, it will probably require the development of new software tools and techniques (as discussed in the previous section) before most customers are able to participate fully in the customization of their own 3D-printed products.

7. Discussion

This chapter discusses the overall implications that digital fabrication and open-source have for the creation of consumer electronics.

Customization

The case studies demonstrate a range of potential customizations in the creation of electronic products. They illustrate multiple dimensions, including process, extent, and motivation.

Customization can occur in either the digital design (pre-fabrication) or the physical craft (post-fabrication) domain. The former deals with aspects of form, including overall shape and surface characteristics. It takes on digital characteristics like precision, reproducibility, and computation. The customizations performed in the digital world can be shared with others and so acquire status as a template from which new designs or customizations can be derived. Customization in the physical world, on the other hand, is specific to an individual product and relates primarily to materials. It acquires characteristics like uniqueness and craftsmanship. Both forms of customization blur notions of authorship. If one person designs the file and another assembles the parts, which one made the product? I'm not sure, for example, how the participants in my speaker workshop would answer this question. When do digital revisions cease to be a customization of someone else's product and become the creation of a new one? The owl speakers seem somewhere on the boundary.

Both digital and physical customization can be undertaken to varying extents. They may be simple, like adding one's name to the bottom of the speakers or selecting a different fabric to wrap them with. Or they may be more complex, like redesigning the overall form of the mouse enclosures or heat-bending acrylic around the curved top surface of the radio. The derivation of the speakers from the radio can be seen as a particularly thorough example. In the digital domain, open-source hardware (i.e. starting from existing designs), when combined with easy-to-use software tools, allows anyone to make small modifications. In the physical world, fabricated parts offer an established structure within which to apply or acquire manual skills. It's possible to trade off labor and skills between the two domains: for example, designing a new circuit board layout to avoid having to manually solder additional components onto an existing one or cutting materials out by hand instead of designing a file with which to laser-cut them.

The motivations for customization vary as well. Some are contingent, like adapting a design to available thickness of plywood. Others are aesthetic, like modifications to the shape or colors of a product. Many are personal, changes to identify the product as made by or belonging to a particular individual - like the souvenir bag in the original Fab FM or the engraved names on the bottom of the speakers. Other changes are functional, like strapping the mouse to someone's hand or hanging the speakers on the wall. Again, the workshops didn't lend themselves to much customization of the electronic circuits themselves; further exploration of changes to them would likely reveal additional motivations for and forms of customization.

Audience

Digital fabrication has different implications for the different groups of people involved in consumer electronics. These are illustrated in both the case studies themselves and the modes of production they suggest.

For customers, the flexibility of digital fabrication processes implies increased choice and freedom in the design and function of their products. This could be a result of an increased selection of 3D-printed enclosures, with diverse shapes and forms, from which the customer simply selects. Or it could take advantage of the opportunities for personal connection to laser-cut products, whether through the use of individual engraving, incorporation of personally-meaningful materials, or through the manual involvement in the construction of the product itself. The small-volume production runs allowed by digital fabrication should make feasible new products or products types that lack the market for mass production, giving consumers more overall choice.

For designers, digital fabrication means changes in both prototyping (which goes far beyond the case studies discussed in the thesis) and production (which is the focus here). Its flexibility and low capital requirements gives them alternatives to traditional business models. Instead of working with or for an established company – or raising the money to become one – a designer can make products for themselves. These can be artisanal electronic devices, handcrafted by the designer become artisan. Or kits, designed and possibly customized on behalf of the designer for final assembly by the customer. Or even custom 3D-printed enclosures for circuits mass-produced by someone else. In general, digital fabrication gives designers the ability to experiment with various processes and models - finding the combination that best suits them and their customers without restriction by the scale and process constraints of mass production.

For engineers, digital fabrication offers similar opportunities to connect directly to customers. Instead of making the insides of mass-produced products or DIY circuits with a narrow appeal, engineers can create finished consumer products themselves. The case studies suggest partnerships between designers and engineers to design, prototype, and produce consumer electronics using digital fabrication.

Themes

Three main themes emerge from this work:

Increased diversity of consumer electronics. Digital fabrication offers the potential for new and creative use of materials, for a greater variety of forms and styles, and for new and different business models and owners. If making a new product requires little investment of time and money, it's easier for someone to experiment with an idea – and to be successful even if it sells only in small quantities. When people can customize the design of existing products, it's possible to tailor them to their specific needs and tastes. As digital fabrication technology improves, its aesthetic and functional possibilities will grow, matching and surpassing various aspects of mass production.

Stronger personal connections with devices. By personalizing or customizing the design of the device, people can share in a sense of authorship of it. Labor invested in the physical production of a device is another opportunity for a feeling of connection and ownership. The possibility for artisanal or small-scale production of consumer electronics means that consumers will have increased opportunities to meet and form relationships with the creators of their devices. All of these possibilities for individual involvement stand in contrast to the impersonal purchasing of the typical products of mass production.

Leveraging the power of software for the creation of physical objects. Because it so simplifies the process of creating physical objects from information, digital fabrication allows the physical objects to benefit from the replicability, scaleability, and flexibility of software. By capturing the products of human creativity in digital form, open-source hardware makes it easier for others to build on it. Software tools can be easily replicated, allowing many people to benefit from developments in interfaces or algorithms that aid in the design of products. They also offer possibilities for work at multiple levels of abstraction, meaning that someone could begin with a set of higher-level building blocks or modules, then descend into more detailed manipulations as their skill or interest increase. The results of these virtual processes are then transformed into physical objects by the process of digital fabrication.

8. Conclusion

In the introduction, I said that digital fabrication is changing the way we make things. This thesis shows the technological and social implications of those changes for the production of consumer electronics. The three case studies shows that it is possible to construct finished products with digital fabrication processes; the workshops that people want and are able to customize and make them for themselves. A review of these experiences illustrates practical lessons for the use of these technologies and, more importantly, methods for improving the software design tools and open-source practices that support them. The thesis proposes four new modes of production for consumer electronic products – an alternative to the mass production that predominates today – and explains how they follow from the capabilities and constraints of digital fabrication technology. Finally, the thesis discusses the overall impact of digital fabrication on consumer electronics: its possibilities for customization and increased diversity of products, its meaning for the people involved, and its ability to leverage the power of software for the creation of physical devices.

These new attitudes and approaches won't replace traditional mass-production – not now and maybe not ever. As digital fabrication continues to improve, many questions remain about how far it can go in the production of consumer electronics. Which, if any, designs will be economically viable to produce in these ways? Who will buy them? How many people have the skills and desire to practice its new modes of production? How complex can the technology get without requiring corporate organization and investment? What other material and aesthetic possibilities exist? To what extent can new tools allow everyone to customize products for themselves? How can the creation of their own devices give people the skills and knowledge to better navigate the technology around them? This thesis, I hope, will motivate and guide others in investigating these questions, providing a core set of possibilities and principles on which to build.

In conclusion then, I envision a new ecosystem of consumer electronic devices, one in which more people participate, in more ways, in the creation of meaningful and diverse products. As in areas like furniture or clothing, where big companies co-exist with artisans and hobbyists in making things for all manner of needs and tastes, so, too, can we make the production of high-tech devices. While we will never be fully free of the constraints of time and money, digital fabrication and open-source hardware provide some of the most promising possibilities for expanding the products and processes that constitute our increasingly technological environment.

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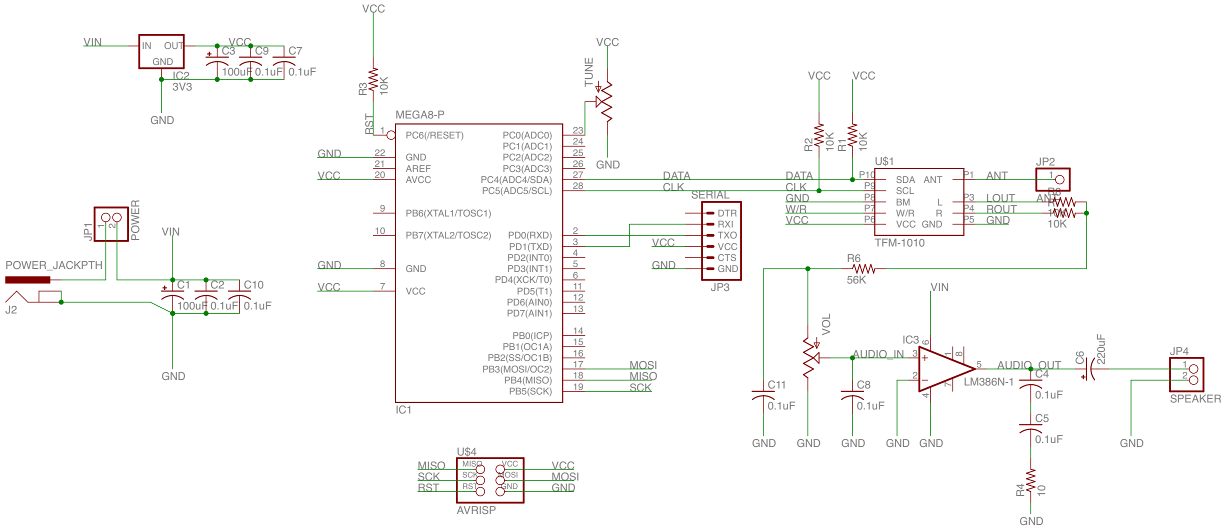
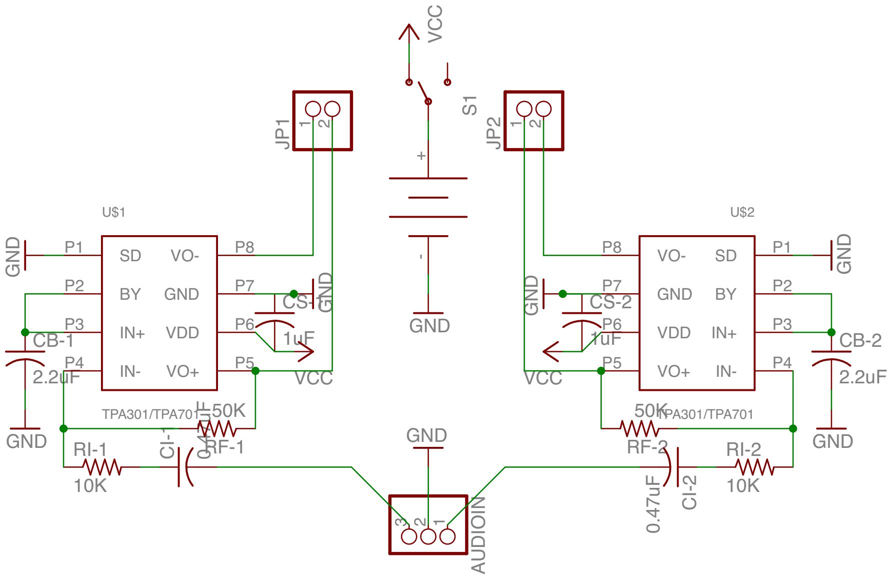
Appendix: Circuit Schematics

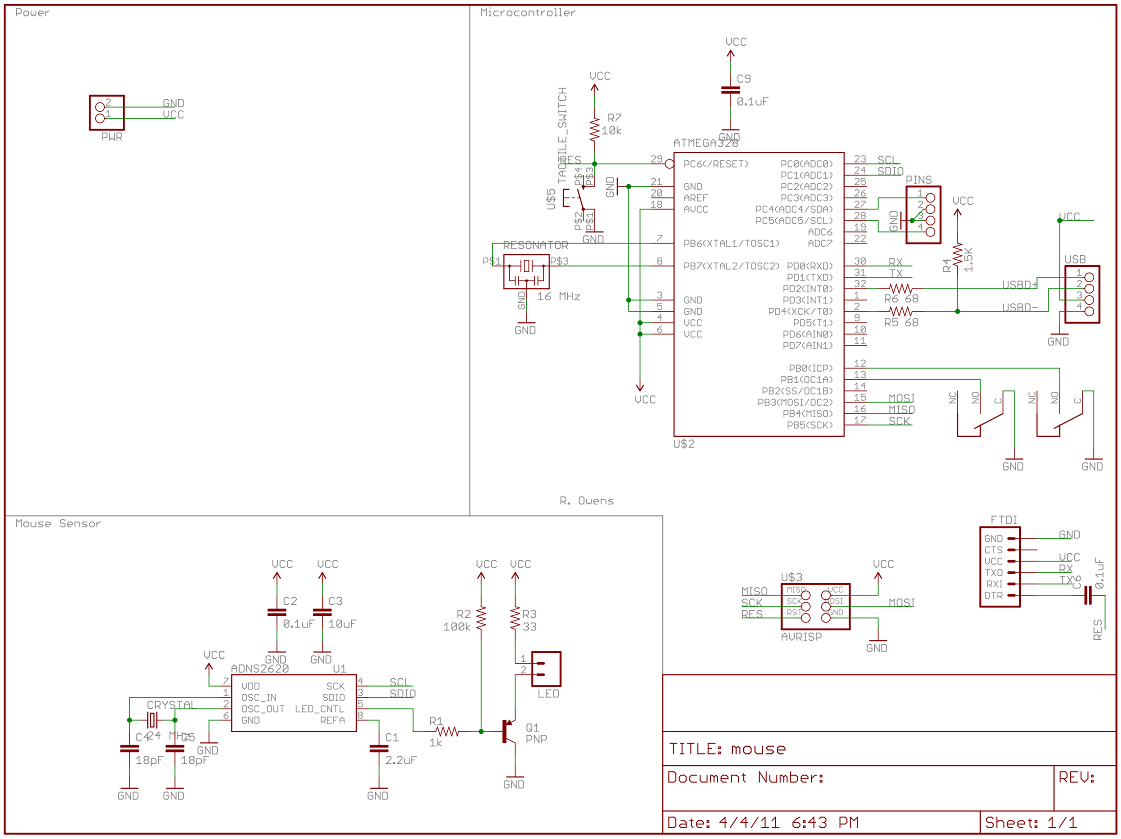
Fab FM



Fab Speakers



Mouse


Power
PWR
GND
VCC
Microcontroller
VCC
C9
0.1uF
GND
ATMEGA328
U$2
PC6(/RESET)
GND
AREF
AVCC
PB6(XTAL1/TOSC1)
PB7(XTAL2/TOSC2)
GND
GND
VCC
VCC
PC0(ADC0)
PC1(ADC1)
PC2(ADC2)
PC3(ADC3)
PC4(ADC4/SDA)
PC5(ADC5/SCL)
ADC6
ADC7
PD0(RXD)
PD1(TXD)
PD2(INT0)
PD3(INT1)
PD4(XCK/T0)
PD5(T1)
PD6(AIN0)
PD7(AIN1)
PB0(ICP)
PB1(OC1A)
PB2(SS/OC1B)
PB3(MOSI/OC2)
PB4(MISO)
PB5(SCK)
SCL
SDIO
PINS
RX
TX
R6 68
R5 68
R4
1.5K
VCC
USBD+
USBD-
USB
GND
MOSI
MISO
SCK
NC
NO
C
GND
VCC
R7
10k
RES
TACTILE_SWITCH
U$5
GND
RESONATOR
16 MHz
GND
VCC
R. Owens
FTDI
GND
CTS
VCC
TXO
RXI
DTR
C6
0.1uF
RES
U$3
AVRISP
MISO
SCK
RES
MOSI
VCC
GND
Mouse Sensor
VCC
C2
0.1uF
C3
10uF
ADNS2620
U1
VDD
OSC_IN
OSC_OUT
GND
SCK
SDIO
LED_CNTL
REFA
SCL
SDIO
CRYSTAL
24 MHz
C4
C5
18pF
18pF
GND
C1
2.2uF
R1
1k
R2
100k
R3
33
LED
Q1
PNP
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