Prototyping Practices in Electromechanical Startups

by

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ABSTRACT

Electromechanical startups contend with significant uncertainty, especially in early stages of development. Prototyping is a critical component through the product development process, and when employed efficiently, can act as a method for mitigating risk associated with product viability for founders and funders. While extensive research has been conducted on prototyping practices in industry, there has been little investigation into prototyping for electromechanical startups.

This research aims to understand current prototyping practices in these environments by answering the following questions. What kinds of prototypes do startups develop? What functions do these prototypes serve? What are the relevant traits that make these prototypes conducive to these functions?

To develop a formal questionnaire, preliminary interviews with two startups were conducted. A case study was also conducted of prototyping practices in 2.009 Product Engineering Processes, an undergraduate course at MIT. Following this, secondary interviews were held with members of three additional startups.

From a sample of 52 identified prototypes, relationships were found between the material categorizations of prototypes and three key functional roles: test, clarify, and communicate. To further understand the prototyping choices of startups, material categorizations were evaluated with respect to eight core prototype characteristics.

Results show that prototypes favored for testing were physically interactive, such as 3D sketches or digitally fabricated models. Inexpensive and easy-to-alter representations (2D sketches, 3D sketches, and CAD) were created to clarify concepts. Visually appealing models (CAD, 2D sketches) were used heavily for both internal and external communication.

Thesis supervisor: Warren P. Seering, Ph.D

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1 Introduction

The electromechanical startup environment exists as a nexus between technological innovation and industry, and is an exciting and precarious space for product development. In the process of bringing brand new products to market, prototyping strategies are crucial in resolving risk and determining the success of these fledgling companies. Understanding these strategies is the central focus of this research. Why do electromechanical startups currently prototype? What forms of prototypes do they create, and why?

1.1 Background

1.1.1 Defining a Prototype

To understand the importance of prototyping in a startup, we must first discuss what a "prototype" means for the purposes of this thesis. Product Design and Development defines a prototype as "an approximation of the product" (Ulrich & Eppinger 2004). The creation of these approximations is crucial for converging on a successful product. The motivations behind their creation spur prototypes to be constructed using a wide variety of methods and materials. In the context of mechanical or electromechanical products, a prototype is generally thought of as a physical representation that "proves a technology or its application" (Wall et al. 1992). In the context of this research, this definition will be expanded to include any working representation of the final product, including both physical and digital models such as sketches or CAD modeling.

1.1.2 The Startup Environment

In "The Lean Startup," Eric Ries (2011) defines the startup as "an organization dedicated to creating something new under conditions of extreme uncertainty". With a failure rate of around 75%, these young companies deal with much higher risk than traditional product development. Unlike established industries, startups have to contend with low initial capital, small staff, less structure, and a limited knowledge base to pull from. Success is dependent on the ability to maximize value under conditions of minimal resources and time. Additionally, because startups are dependent on outside funding from investors, they must continually

pitch their concept and prove the value of their product to external parties. Under these volatile conditions, prototypes are crucial tools for resolving risk. Utilized correctly, they can generate critical information with minimal investment required. They also serve as proofs of concept for investors and interested parties, and are instrumental in creating buy-in incentive.

1.2   Thesis Organization

This thesis contains six chapters. Chapter 1 introduces the themes of interest (product development, prototyping, and the startup environment), describes the motivation for the study, and explains the scope of the research. Chapter 2 discusses literature relevant to two key topics: the role of protyping in product development, and product development in startups. Chapter 3 details the research approach and methods. Chapter 4 presents the results of the study, and explains the framework for categorizing prototypes. Chapter 5 provides a conclusion, and proposes opportunities for future research.

1.3   Research Goals

1.3.1   Academic Motivation

Exposure to the entrepreneurial world is inevitable for a student on the MIT campus. As an undergraduate, my first introduction to startups and the full product development cycle came from 2.009 Product Engineering Processes, a capstone course for mechanical engineering majors. In 2.009, teams of 16-18 students work together in mock-industry conditions to deliver an alpha prototype of a product throughout the course of a semester. At the end of the semester, it is not uncommon for teams to continue with the development of their products and pursue the startup route.

With deliverables and presentations due every few weeks, students are expected to operate under an accelerated timeline and prove the value of their products to a panel of external parties (mentors, professors, users, etc). Unlike in startups, there is a significant amount of prescribed structure, funding, and mentorship available. In this setting, the importance of testing hypotheses is emphasized over assumption, and prototyping is taught as a tool for resolving uncertainty and risk as early as possible. This guided foray into fast paced product

development inspired further exploration into effective practices under conditions of even more uncertainty: those of the startup environment.

1.3.2 Research Scope

Previous literature has explored effective prototyping practices for industry (Wall, Ulrich & Eppinger 1992,) as well as startups of the software variety (Reis 2011). However, similar research for hardware startups has yet to be conducted. The startup environment differs wildly from the world of industry, and unlike in software, the development of a hardware product involves physical prototyping. This requires different skill sets, material considerations, and timelines. Because of these key differences, these previous studies are not directly applicable to the space of hardware startups.

The research described in this paper has been conducted to address this gap, and focuses primarily on prototyping practices in early-phase electromechanical startups around MIT. Experiences with prototyping in analogous academic settings such as 2.009 were used in formulating, but not testing, the hypotheses presented in this study.

1.3.3 Research Questions

The first goal of this research has been to understand the current roles that prototyping plays in the electromechanical startup environment. What are the categories of prototypes that startups employ? What different functions does each category serve? The second goal has been to study how the characteristics of these prototypes inform their function. What traits make them effective in a start-up setting? The final goal has been to recognize what constitutes an effective prototyping strategy for startups. Based on the answers to the questions posed above, what prototype should startups use in a given situations?

1.4 Research Approach

To address the goals of this research, a literature review was conducted on product development processes, effective prototyping practices, and lean startup methodology. For first-hand exposure to the startup setting, preliminary interviews were performed with two

startups. Additionally, a case study of prototyping practices in the 2.009 context was conducted. Following these interviews, a set of hypothesis were formed regarding prototyping startup settings. Interviews were conducted with three additional startups, as well as follow up interviews with the initial sample.

2 Literature Review

This chapter reviews a collection of literature that explores two central themes: the roles that prototyping play in the product development process, and effective product development practices in small scale start-ups.

2.1 Prototyping in Product Development

The classification of prototypes throughout the industrial product development process has been extensively explored in literature. Ulrich & Eppinger (2004), provide an overview of the functions of prototyping in Chapter 12 of Product Design and Development. A prototype is defined as "an approximation of the product along one or more dimensions of interest." Two relevant dimensions for classification are described. The physical versus analytical dimension refers to the method of approach: whether the prototype is modeled tangibly or using mathematical methods. The comprehensive versus focused dimension refers to scope: if the model embodies all of the attributes of the finished product, or selectively targets characteristics.

A model for evaluating prototyping technologies in the context of industrial manufacturers was developed by Wall, Ulrich & Eppinger (1992). The study focused on a set of four technologies frequently used in industrial contexts: CAD solid modeling, stereolithography (3D printing), computer numerically controlled machining, and rubber molding. Their method evaluated processes along three key dimensions - part performance, unit cost, and lead time - to determine the best process under specific conditions.

Similarly, the effect of design tool use on innovation in engineering teams has been investigated by Jang & Schunn (2013). Upon examining design tool choices in a sample of 43 interdisciplinary design teams, correlations were drawn between patterns of tool use and success. Jang and Schunn concluded that a tool's effectiveness was time-dependent. The late adoption of physical prototypes was a consistent trait of unsuccessful design teams. It was also observed that tools were instrumental in facilitating communication, as successful teams "used tools supporting collaborative work more often throughout the process than did unsuccessful teams."

The importance of communication in product development is discussed in Olechowski

(2012). In her thesis, Olechowski explores the role of transparency (or open communication) in product development risk management. Transparency was found to be "a vehicle for an accurate shared representation of the current state of the product development project," a method for facilitating collaboration and aligning efforts toward critical tasks. A detailed exploration of prototypes in relation to communication is conducted by Carlile, 2002. The paper introduces the concept of a boundary object as "a means of representing, learning about, and transforming knowledge to resolve the consequences that exist at a given boundary." In product development, knowledge exists as both a barrier and source for innovation, and is often localized within individual functional groups. Prototypes and other boundary objects serve as a means of traversing those barriers between groups to establish shared languages and methods for dealing with differences and dependencies.

2.2   Product Development in Start-ups

As mentioned in the introduction, industrial product design is traditionally modeled as a linear process. The product is incubated and refined as it flows through the six phases of planning: concept development, system design, detail design, testing/refinement, and production (Ulrich & Eppinger, 2004), at which point the product is ready to enter the marketplace.

However, startups experience a different set of constraints than those found in industry. This disparity has given rise to a new product development methodology for entrepreunerial small companies, which is described as the lean startup movement (Ries, 2011). This model introduces the implementation of the "build-measure-learn feedback loop" to deliver a minimum viable product, a version of the product that generates the most knowledge with the least effort. This cyclic model emphasizes customer driven practices, using rapid iteration and testing to maximize feedback and minimize the risk associated with uncertainty. By constantly reevaluating the product and collecting customer feedback, the build-measure-learn loop reduces waste in the form of unnecessary work. While the lean startup focuses primarily on software products, the core practices are applicable for driving a successful electromechanical startup.

In addition to the lean startup model, there are other product development processes designed to drive rapid innovation. These processes include Design Thinking (Plattner et

al., 2009) and the Rapid Innovation Cycle (RIC) (McCoy et al., 2012).

Design Thinking is a user driven innovation strategy developed by IDEO. While it is a generally linear model, it "makes use of extensive user research, feedback loops and iteration cycles" (Mueller & Thoring, 2012). Like the lean startup method, design thinking emphasizes rapid iteration and testing early. This model aims to generate innovation in general, and can thus be applied to product development in startups.

The Rapid Innovation Cycle is an innovation process designed to generate sustainable and profitable innovation in a company or startup (McCoy et al., 2012). The RIC focuses on market testing, and employs an iterative four step process: opportunity recognition, solution selection, experimental results, market experimentation. In a study conducted by McCoy et al. (2012), the RIC process was successful in reducing invested time and cost.

3 Research Methodology

A series of interviews and case studies were conducted to narrow my area of interest from efficient product development in startups, understand the space of prototyping in startups, and ultimately to address the following questions:

- What types of prototypes do startups develop?

- What functions do these prototypes serve?

- What are the relevant traits that make these prototypes conducive to these functions

Interview candidates were recruited through professional and academic connections, including with the help of the Martin Trust Center. As a result, they are all in some way affiliated with MIT.

3.1 Preliminary Interviews

To gain an understanding of general startup structure and prototyping practices, a preliminary set of 23 interview questions were created (see Appendix A for a copy of the preliminary interview protocol). These questions were divided into four categories:

- **Background**: An understanding of the backstory for the startup. Contextual information regarding the company's product and the current team.

- **General**: A high level overview relating to the volume of prototypes, and context of prototype development.

- **Execution**: A detailed exploration of the implementation of specific prototypes, including tools, materials, turn-around time, and team input.

- **Function**: An investigation of what roles the prototypes served throughout the product development process.

3.1.1 Interview Structure

Members from two startups were interviewed with questions described above. Four subjects participated in total, each of whom had engineering or business backgrounds. Based on their areas of specialty, subjects played varying roles in their respective startups. While the protocol was instrumental in guiding discussions, interviewees were encouraged to provide commentary and insights outside of the prescribed questions. One-on-one interviews were conducted in person, and lasted for approximately an hour.

3.1.2 Case Study of 2.009

To further explore the importance of prototypes, a case study was conducted of my team's experience in the 2.009 Product Engineering Processes course. The set of preliminary questions were answered based on my own recollections, as well as the extensive documentation generated during the class in the form of notebook entries, photography, videography, mentor feedback, and presentation materials.

The structure of 2.009 aims to simulate an environment similar to that of startups, where student teams are tasked to create a new product under high pressure, limited time conditions. However, due to the nature of the academic setting, the teams themselves can not be accurately modeled as startups. The course prescribed structure in the form of specific milestones and corresponding deliverables, and provided an abundance of funding as well as constant mentor and instructor feedback, all of which are unlikely to be found in a startup settings.

Nevertheless, studying the 2.009 experience was beneficial for understanding prototypes in the context of constrained product development. This case study provided information for formulating hypotheses, but was not used as data for the testing phase.

3.2 Categorization of Prototypes

Using the information obtained from preliminary interviews and the 2.009 case study, two methods for categorizing prototypes were developed. These include a material categorization, and a functional role approach.

Currently, several basic methods of labeling prototypes exist. One system delineates with respect to the timeline of the project, with labels such as "proof-of-concept", "alpha prototype" and "production-ready product". Another standard approach is to classify based on a prototype's function, with categories such as "user experience prototype", "visual prototype", and "functional prototype." However, neither of these fit this study particularly well. The timeline-dependent method of classification maps to a linear model of product development that does not accurately capture the iterative processes employed by most startups. While creating a functional breakdown of the prototyping space is one of the goals of this research, I was interested in understanding the functions through a different lens than the existing categorization provided.

3.2.1   Material Approach

To investigate the functionality of prototypes, a method of categorization was created to focus on a prototype's relevance with respect to its physical traits. Two defining characteristics of a prototype are the materials and technologies used in crafting it. The classification chosen directly reflects this:

- **2D Sketches**: Two-dimensional visual representations produced either by hand (using pen, markers, paper, etc.) or digitally (using software such as Illustrator or Photoshop).

- **3D Sketches**: Three-dimensional physical representations constructed using inexpensive, easily manipulable materials (such as cardboard, foam core and blue foam). These are also known as sketch models.

- **CAD Models**: Digital solid representations modeled through the use of computer systems such as Solidworks or Rhinocerous, which involves the definition of dimensions and constraints.

- **Digitally Fabricated Models**: Physical models produced with rapid prototyping (additive or subtractive production processes). Requires the use of 2D illustration or 3D modeling software to produce a digital file prior to the generation of the physical model.

- **Realistic Material Models**: Prototypes created using materials and tools that could be used in final production.

3.2.2 Functional Roles

From preliminary interview responses and literature reviews, a hypothesis was developed regarding three core functionalities that prototypes serve:

- **Test**: Prototypes are often used for performing tests to resolve known concerns or to discover unknown problems. This pertains to a wide range of categories, such as technical feasibility (is it physically or technically possible to achieve desired performance), functional performance (how does the design perform under certain conditions), or user testing (how do users respond to certain design configurations).

- **Clarify**: In some cases, prototyping is undertaken by the designer to solidify details of the design. These prototypes are often approached without a clear, specific plan of action. Instead, the act of prototyping fuels ideation and enables rapid idea generation. The prototypes themselves serve as tools for individuals to understand the design space, compare possible configurations, and emerge with clarified direction of interests.

- **Communicate**: Certain prototypes serve as boundary objects, and are used to aid communication between different stakeholders in the product. This includes the core startup team, as well as external parties such as investors, mentors, and potential users. The makeup of each startup team includes individuals who play different functional roles, depending on their backgrounds. In most of the startups that I interviewed, this involved a differentiation between business and engineering. It is important to consider communication at these inner boundaries between the functional groups of the team, as well as at the outer boundary between the team and external stakeholders.

3.3   Secondary Interviews

Based on the methods for categorizing prototypes explained above, a second interview protocol was developed to collect data for testing the hypotheses (see Appendix B). This included a shorter set of 12 interview questions, which were kept relatively open-ended so as not to lead subjects to any expected answer. Questions were divided into three main groups:

- **Background**: An overview of the company's product and the current stage of development.

- **Team**: An understanding of the size and breakdown of the overall team, as well as the role of the interview subject.

- **Purpose**: A detailed description of prototyping practices in the startup, including motivation, material and tool use, effects on communication, and lessons learned.

3.3.1   Interview Structure

Second round interviews were conducted in a similar fashion to the preliminary round. Five subjects were interviewed, representing three startups in total. All individuals had either an engineering or business background. As was the case in preliminary interviews, the roles that subjects played in their respective startup varied depending on their background. One-on-one interviews were conducted in person or via video chat, and lasted for approximately an hour.

4   Results

The results of this research are presented below in the form of individual case studies for each startup. Following this, overall observations from these case studies are included.

4.1   Case Studies

Each study lists the prototypes identified, including the corresponding material categorization and functional purposes. Prototypes are listed chronologically based on time of creation. If multiple prototypes were created simultaneously as variations of a single concept, served the same functions, and were produced using the same methods, they were grouped together as a single instance (for example: a collection of sketches was considered one instance of a 2D sketch). The startup's prototyping habits and other insights identified by the interview subjects are subsequently explained.

4.1.1   Case 1: Avatech

Avatech is a company interested in promoting proactive avalanche safety. Their current product is a portable device that allow users to assess avalanche risk in real time while navigating risky terrain. The Avatech team consists of five members, including three co-founders that act as CEO, lead engineer, and lead engineer/designer, as well a lead application developer, and a lead electrical engineer. The initial proof of concept was created during a graduate product design class at MIT in Spring of 2013. Since then, Avatech has been working to optimize and integrate the designs. They are currently in the process of redesigning for manufacturing.

Two co-founders of the Avatech team were interviewed, who filled engineering and design roles in the company. During the interviews, fourteen prototyping instances were identified.

The Avatech team utilized 2D sketches to clarify design options for personal resolution, and to communicate within the engineering team. They prototyped 3D sketch models to quickly assess sensor options and clarify the product form. Materials such as blue and green foam allowed the designer to rapidly generate and test variations of ergonomic handle designs.

#	Material Categorization	Test	Clarify	Int Com	Ext Com
1	2D Sketch		x		
2	2D Sketch		x	x	
2	2D Sketch		x	x	
4	3D Sketch	x			x
5	Digital Fabrication				x
6	Digital Fabrication	x		x	
7	3D Sketch	x			
8	CAD		x	x	
9	Digital Fabrication	x		x	
10	CAD		x	x	x
11	3D SKetch	x			
12	Realistic Materials	x			x
13	Digital Fabrication	x			
14	CAD			x	x

Table 4.1: Prototypes and corresponding functional roles for Avatech

CAD modeling was used to further explore industrial design options. Additionally, CAD was often employed after testing physical prototypes, to solidify and communicate ideas both internally and externally to manufacturers. Digitally fabricated models were created for explaining the team's value proposition to external stakeholders, as well as conducting detailed tests of sensor performance. In order to optimize or explore certain dimensions, simultaneous batches of prototypes with small variations were built.

Interview subjects also noted that instead of building new prototypes for communication with external parties, they occasionally reused previously built prototypes. Digitally fabricated prototypes that may not have functioned as intended were sometimes repurposed as visual props for communication.

4.1.2 Case 2: Ecovent

Ecovent Systems focuses on efficient and comfortable home temperature control. Ecovent is a system of vents that allows users to control the temperatures of individual rooms wirelessly. Their product has three core components: wireless vents, a suite of plug-in sensors and a digital application. Their team comprises of six members, including a CEO, CFO, CTO, and three part time engineers responsible for electrical engineering, software architecture, and android development. Ecovent has completed an alpha prototype, which is being

installed for user testing. Based on this feedback, they expect to deploy beta systems in multiple homes by the end of the year.

Two co-founders of the Ecovent team were interviewed, both of who were responsible for business development in the company. Collectively, they identified six prototype instances.

#	Material Categorization	Test	Clarify	Int Com	Ext Com
1	CAD		x	x	
2	Digital Fabrication	x			x
3	3D Sketch	x	x		
4	3D Sketch	x	x		
5	CAD			x	
6	Digital fabrication	x			x

Table 4.2: Prototypes and corresponding functional roles for Ecovent

Due to the founders' previous experience with hardware startups, and easy access to necessary technology, Ecovent used CAD modeling and digital fabrication to create a miniature four-vent model that served as their first prototype. This was used initially for testing feasibility, and subsequently for communicating vision to mentors and investors. 3D sketch prototypes were used in performing quick tests and optimizing important performance parameters, such as noise level and sensor configurations.

A digitally fabricated prototype was created for user testing and communicating product vision with external stakeholders. Digital fabrication was chosen due to the small scale of production, and relative speed and accessibility of the technology. Ecovent will be creating realistic material models for demonstration and user testing in the immediate future.

4.1.3   Case 3: Sistene Solar

Sistene Solar designs aesthetic solar installations. Their product consists of a system of modular solar tiles than can integrate with street furniture products. There are two co-founders, both of whom hold an MBA from the MIT Sloan program, as well as a lead engineer, an artist, and an engineering intern. The company was founded in the summer of 2012, and have just completed an alpha prototype this past January. They are looking for a pilot site in Boston, and hope to begin field testing as soon as possible.

Two members of the Sistene Solar team were interviewed, including one co-founder and one intern. The co-founder was responsible for business development, while the intern worked on engineering and aesthetic design. Collectively, twelve prototypes were identified.

#	Material Categorization	Test	Clarify	Int Com	Ext Com
1	2D Sketch	x			x
2	2D Sketch		x	x	
3	3D Sketch	x			
4	CAD			x	
5	Digital Fabrication	x			
6	CAD			x	
7	Realistic materials	x			x
8	Digital fabrication	x			x
9	CAD				x
10	2D sketch		x	x	x
11	Digital fabrication	x			
12	Realistic materials	x			x

Table 4.3: Prototypes and corresponding functional roles for Sistene Solar

Throughout product development, Sistene Solar used 2D sketches (pen and paper drawings, renderings, and photoshop images) to assess user needs, design and select aesthetic layouts, and generate engineering options. Sketches were identified as quick and inexpensive (often the most valuable prototype at the time), and were used to create a visually interactive dialogue between two parties. A round of four 3D sketches were created to rapidly investigate options for connections between tiles.

Upon settling on rough concepts, CAD modeling and digital fabrication methods were used to prototype. Because the ease and strength of connections are core functional requirements for the product, tolerances were a critical consideration. The level of specificity that these two methods provided allowed for accurate testing and communication of dimensional options. The production of digitally fabricated prototypes was often a bottleneck that delayed progress, due to the startup's limited access to the technology.

Realistic materials were used for considering surface treatment methods, which are critical for accomplishing the aesthetic vision of the final product. These prototypes were used in investor meetings to successfully communicate vision.

4.1.4 Case 4: Jon Lou

Jon Lou is a lifestyle brand that integrates fashion and technology. Their current product is a luxury leather purse that charges devices and lights up upon opening. They are a team of five, including two co-founders, a marketing director, a director of business development, and an engineering intern. Jon Lou has produced a functional alpha prototype, and is currently in the process of working on a beta version of the product, which will be sold and used to collect user feedback.

Two members of the Jon Lou team were interviewed, including a founder and an intern. The founder was responsible for business development and worked on product design and engineering in conjunction with the intern. Collectively, twelve prototypes were identified.

#	Material Categorization	Test	Clarify	Int Com	Ext Com
1	2D Sketch				x
2	2D Sketch				x
3	CAD				x
4	Realistic Materials	x			x
5	2D Sketch		x		x
6	Digital fabrication	x			
7	2D sketch	x	x		x
8	2D sketch		x		x
9	CAD				x
10	Realistic Materials	x			x
11	3D Sketch	x			
12	Digital fabrication	x			

Table 4.4: Prototypes and corresponding functional roles for Jon Lou

Traditionally in the fashion industry, sketches are the communication method of choice. Because Jon Lou's current product is an exploration in fashion design as well as engineering, a significant portion of the prototypes were 2D sketches or collages. These were used both to clarify designs within the team and to communicate with external stakeholders. Some were created as a means of convey vision to investors or users, while others were used to explain design details for patents or production. Due to limited access to 3D modeling software or a full time engineer, these were often used in the place of CAD models.

Instead of internally prototyping physical models to test individual design components, the team decided to outsource the production of realistic material prototypes to external

manufacturers. While advised to prototype a "minimum viable product" for testing, as perfectionists, Jon Lou felt that a prototype not manufactured to their final vision would not accurately convey the desired design. Unfortunately, the design intentions did not necessarily translate in these prototypes, and this proved to be an expensive and time consuming way of discovering design problems.

Upon reflecting on the prototyping journey of her company, the CEO noted that prototyping small components of the product was necessary to save time and money. This resulted in a quick round of 3D sketch and digitally fabricated prototypes.

4.1.5 Case 5: Pegasense

Pegasense Inc. is developing an equine leg injury prevention and detection system. This product consists of special splint boots that monitor the temperature of a horse's legs, an alert device that allows riders to access temperature data, and a charging station for the boots. The current Pegasense team consists of five founding members, an acting CEO, user experience designer, lead software engineer, lead hardware engineer and head of research & development. The product concept stemmed from 2.009 (an undergraduate product design class at MIT,) in the fall of 2013. An alpha prototype was delivered by the end of the semester. Since then, the team has created an alpha-2 prototype, and is undergoing beta development in preparation for a paid round of testing this upcoming summer.

A founder of the Pegasense team was interviewed, who played both engineering and customer facing roles in the company. She identified eight prototypes that were developed post 2.009.

#	Material Categorization	Test	Clarify	Int Com	Ext Com
1	2D Sketch		x	x	
2	Digital Fabrication	x			
3	Digital Fabrication	x			
4	Digital Fabrication	x			x
5	Digital Fabrication	x			x
6	Realistic	x			x
7	CAD	x			x

Table 4.5: Prototypes and corresponding functional roles for Pegasense

In the five months since the completion of the alpha prototype, the Pegasense team has

created an alpha-2 iteration out of realistic materials for robustness and user testing. In the process of producing this prototype, the team rapidly produced 2D sketches to clarify and communicate geometry and organization of components within the boot. Because the boot is a soft wearable technology, CAD was found to be inadequate for understanding fit. Several rounds of digital fabrication were subsequently used to perfect electronic placement in the boot.

4.2 Overall Observations

4.2.1 Material Categorization v. Functional Roles

From the case studies presented above, correlations can be found between the material categorization of a prototype and its functional roles. Cumulatively, 52 instances of prototyping were identified. Of these, 29 prototypes were used to test, 14 to clarify, 16 to communicate internally, and 27 to communicate externally. For each category, Table 4.6 shows the number of prototypes and percentage that were identified for each functional role.

In the sample of startups interviewed, instances of digitally fabricated prototypes were created most frequently, followed by CAD models and 2D sketches. Two-dimensional sketches were produced most for clarification and communication, while three-dimensional sketches were used primarily for testing. CAD models were predominantly created for internal and external communication. Depending on the user's proficiency with the 3D modeling, they also helped clarify design concepts. Almost all digitally fabricated prototypes were generated for testing, but some functioned also as props for communication. All realistic material prototypes were utilized both in testing and external communication.

Material Categorization	Total #	Test (%)	Clarify (%)	Int Com (%)	Ext Com (%)
2D Sketch	11	18%	73%	36%	64%
3D Sketch	6	100%	33%	0%	17%
CAD	14	7%	29%	71%	50%
Digital Fabrication	15	93%	0%	13%	40%
Realistic Materials	6	100%	0%	0%	100%

Table 4.6: Breakdown of functional roles for each material categorization

It was found that a single prototype often served multiple functional roles. Therefore,

it is also important to examine individual functional roles, and the material breakdown of prototypes in each of these groups. Table 4.7 demonstrates, for a given functional role, the percentage of prototypes in each material category. It was observed that 48% of prototypes created for testing were digitally fabricated, while 57% of those used in clarification took the form of 2D sketches. For both internal and external communication, CAD models and 2D sketches were the most pervasive forms of prototyping.

Function	2D Sketch	3D Sketch	CAD	Digital Fabrication	Realistic Materials
Test	7%	21%	3%	48%	21%
Clarify	57%	14%	29%	0%	0%
Int Com	25%	0%	63%	13%	0%
Ext Com	26%	4%	26%	22%	22%

Table 4.7: Breakdown of material categorization for each functional role

4.2.2 Relevant Characteristics of Material Categorization

To understand the distribution of prototypes across each function, a set of eight key prototype characteristics were identified: cost, production time, precision of information, physical interactivity, ease of modification, aesthetic appeal, accessibility & familiarity of technology, and similarity to final product. These characteristics were identified by interview subjects as priorities when choosing methods of prototyping, and were corroborated by my personal experiences in product development.

A pugh matrix is shown below (Table 4.8), comparing each prototype category along these eight dimensions. Because all interviewed startups are MIT based, their cost for CAD software and digital fabrication is considered negligible due to the availability of subsidized resources on campus. By characterizing a prototype's performance along dimensions as a consequence of their material categorization, we can begin to explain prototyping choices for each functional role.

Material Categorization	Cost	Time	Precision	Physical Interactivity	Ease of Modification	Aesthetic	Accessibility	Similarity
2D Sketch	+	++	-	-	+	0	++	0
3D Sketch	0	+	-	+	+	-	+	–
CAD	0	0	0	0	0	0	0	0
Digital Fabrication	0	-	+	++	-	+	-	+
Realistic Materials	–	–	+	++	–	+	–	++

Table 4.8: Pugh chart comparing eight relevant characteristics

Unlike in industry, the startups interviewed did not have a preexisting knowledge base of proven technology or methods to pull from. Additionally, the interviewed subjects had little to no industry experience. Under these conditions, extensive testing is required to understand physical constraints, and optimize along important parameters. This results in a prioritization of physically interactive prototypes such as 3D sketches, digital fabrication and realistic material models. To decide what prototypes to create within this subgroup, the subject of the test must be considered. The type of investigation informs parameters such as cost, time, required precision, and similarity to final product, which are used in choosing prototypes. For example in the case of Sistene Solar, a prototype designed to test tolerancing required a high degree of precision at a reasonable cost, leading the company to choose a digitally fabricated model.

While attempting to clarify a design, time and ease of modification are key considerations. Prototypes that are quick to develop and easy to manipulate enable rapid idea generation. By producing and comparing many concept variations, designers and engineers are able to explore the design space and focus in on specific directions of interest. The identified characteristics favor the use of 2D sketches and 3D sketches for clarification. CAD models were also used to a lesser extent, depending on the subject's proficiency with the software.

Startups are constantly challenged to explain and sell their ideas to external stakeholders. Additionally, because they are often in the process of solidifying design goals and execution of the product, internal communication is also critical for ensuring a shared team vision. Because of this, clear aesthetics are crucial when creating prototypes that aid communication. It was observed that 3D sketches, which are frequently rougher and less aestheticized, were seldom used in communication both internally and externally. Instead, CAD models were favored for aiding both internal and external communication. Additionally, due to their similarity to the final product, all realistic material models that were created were used in external communications. However, due to considerations of cost and technology accessibility, there was an overall scarcity of realistic material models across all the interviewed startups.

5   Summary and Conclusions

Prototyping is a critical component of product development, and effective practices have been widely discussed in the context of industry-based product design. However, prototyping strategies for startups is a newer area of study, and has not been extensively researched in previous literature. This work investigates current prototyping practices in electromechanical startups, including correlations between the sets of prototypes created, their corresponding functions, and the relevant characteristics that they exhibit. Nine interviews were conducted, including members of five startup companies.

5.1   Research Limitations

When discussing results, it is important to consider the limitations of the study. While the electromechanical startups interviewed had diverse areas of focus, they all shared an affiliation with MIT. As a consequence, these startups constitute a very specific subset that is not necessarily representative of all electromechanical startups. The affiliation to an engineering university provides subsidized access to many resources that may otherwise be less available, such as CAD software, digital fabrication technology, and mentorship.

Additionally, it is important to note that the level of specificity is not standardized across all case studies. Even within a single startup, the account of prototyping often varied greatly depending on the roles that interview subjects held. Therefore, it is unlikely that the identified prototypes constitute a comprehensive sample for any of the startups. During interviews, it was also found that subjects were not equally inclined to discuss all categories of prototypes. They were less likely to remember or identify sketches that were created, while prototypes produced with realistic materials were elaborated on in much more detail.

5.2   Current Practices

From the five startups studied, 52 prototypes were identified, most of which served multiple functions. Of these, the greatest number of prototypes were produced for testing, while the least were created to clarify concepts designs.

From the sample acquired, it was observed that prototypes produced by digital fabrica-

tion and CAD modeling were favored overall, possibly due to the level of precision available at a low cost. Prototypes that were developed for testing were found to be predominantly physically interactive, but varied along the dimensions of time, cost, precision, and accessibility depending on what aspects of the product were being investigated. Prototypes that were inexpensive and easy to manipulate such as 2D sketches, 3D sketches, and CAD, were created to clarify concepts, while visually appealing prototypes were used heavily for both internal and external communication.

5.3   Future Research

In the development of this thesis, many relevant observations and topics of interest were left unpursued. These opportunities for future research are detailed below.

5.3.1   Increased Scope

The sample of startups interviewed in this study is not large enough to extrapolate any statistically relevant results. Additionally, their affiliation with MIT results in a skewed subset. By conducting more interviews with startups with different origins, a larger data set could be collected to better understand the prototyping processes of electromechanical startups outside of the MIT bubble, and perhaps arrive at a concrete understanding of best practices.

5.3.2   Effect of Industry and Technology

It was found that the type of industry and technology that the startup was working with had an effect on the categories of prototypes that were created. For example, due to the nature of the fashion industry, sketches can be more helpful than CAD models for wearable technologies. Certain technologies may also require a higher degree of specificity in prototyping than others. Instead of blindly grouping all electromechanical startups together, further exploration into the effects of technological differences in prototyping should be explored.

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A Preliminary Interview Protocol

Introduction

Thank subject for taking the time to meet with me. Introduce myself and thesis topic: understanding prototyping practices in startups with electro-mechanical products.

Background

1. What is the name and focus of your start-up?

2. What products have you worked on?

3. What is your role on the team?

4. Could you explain your product development process?

5. What stage of the product development process is the product currently at?

General

1. What prototypes have you created?

2. What stages of the process have you created prototypes for?

3. How many? What types of prototypes?

4. How valuable were they? What did you learn?

5. What defines a successful prototype?

Execution

1. How did you choose which prototypes to build?

2. How many individuals give input on a prototype?

3. What technologies do you use for each prototype?

4. What materials do you use?

5. What was the average turn-around time for a prototype?

6. What percentage of time was spent on prototyping? What was the budget?

Function

1. How did prototypes play into the decision making process?

2. Did prototypes function as tests of hypotheses?

3. Did prototypes result in the creation of knowledge/idea generation?

4. Were there prototypes that served multiple functions?

5. Did prototypes affect communication?

6. Were prototypes shared within your immediate group and/or externally?

7. Have you kept prototypes as references after the completion of the project?

B   Secondary Interview Protocol

Introduction

Thank subject for taking the time to meet with me. Introduce myself and thesis topic: understanding prototyping practices in startups with electro-mechanical products. Request permission to take notes on laptop.

Background

1. What is the name and focus of the start-up?

2. What stage of the product development process is the product currently at?

Team

1. What is the size and breakdown of the team?

2. What is your role on the team?

Purposes of Prototypes

1. Please describe the prototypes you built (including sketches/cad/excel files)

- Turn-around time?

- Materials/tools used?

- Cost?

- Contributors?

- Stage of product development?

2. How did you choose which prototypes to build?

3. What functions did these prototypes serve?

- What uncertainties did you resolve?

4. Did you (the company) learn what youd hoped? Did you learn useful things other than those that youd planned for?

5. What additional tools or exercises did you use throughout the design process?

6. Which prototypes were most successful and why?

7. Were prototypes shared within your immediate group and/or shared externally?

8. What tools/props are used when communicating with external groups?