Rapid Prototyping Method for a Microfluidics Device

by

Kameron L. Klauber

Submitted to the
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ABSTRACT

The product design process can be described as a number of steps taken to turn an idea into a reality. One particular design process of creating a microfluidics device was studied and analyzed. A device containing channels for fluid flow presents a number of challenges for designers. The particular device in this study had a number of specifications, which include a small scale, a necessity to hold fluid, and a desire to control fluid flow. The overall process for developing this product can be broken into the idea, concept development, 3D CAD, simulations, 3D prototyping, assembly, and biochemistry testing. This is one process that has been completed and studied to identify certain design decisions related to this particular device. Further testing and future design iterations will be needed to prove the success of this particular device.

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1. Introduction

Because of new rapid prototyping technologies, new innovations can be transformed from concept to reality in remarkable time. Computer aided design software and 3 dimensional printers have revolutionized the process of product design and rapid fabrication. This thesis focuses on the development process of a microfluidics device for drug delivery. Because of the sensitive nature of the project at the MIT Institute for Soldier Nanotechnologies this paper is broadly conceptual and focuses on the design process rather than the actual design.

1.1 Microfluidics

Microfluidics is an interdisciplinary field focused around the behavior of fluids at a very small (usually sub-millimeter) scale. Our interest in microfluidics stems from the desire to characterize fluid behavior through very small channels in order to optimize fluid motion within a manually powered device. Microfluidics introduces a unique set of challenges to product design for a variety of reasons. This paper will address those challenges and present a number of design decisions based on those challenges.

1.2 Overview of Process

The process for the rapid prototyping of a particular microfluidic device can be broken into seven steps: the idea, the concept development, the computer-aided design, the simulations, the 3D prototyping, the assembly, and the bio-chemical testing. The process is shown in Figure 1.

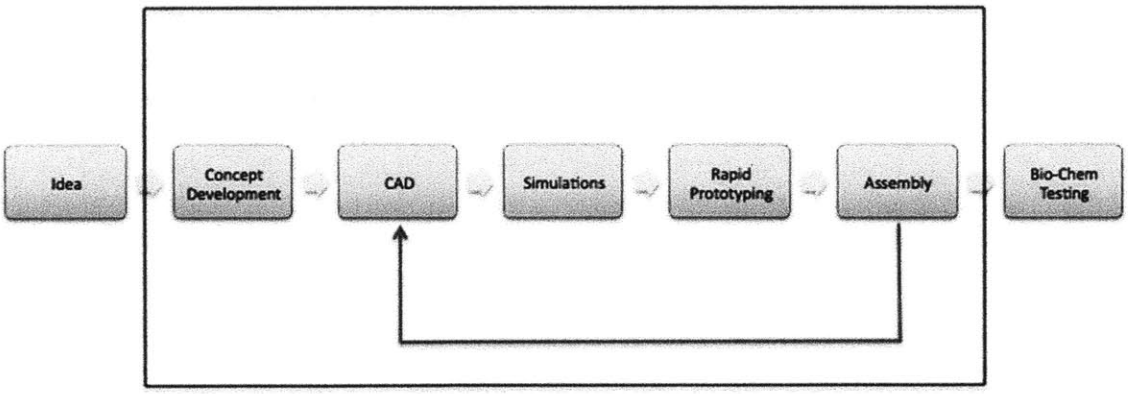

Figure 1. A flow chart showing the development process. For the scope of my work, I mainly focused on the design through the assembly of the product, as shown by the black box. Additionally the blue arrow shows a feedback loop used in our process.

In order to create a successful product the problem statement must be well defined. There must be a clear motivation for the work before the work is started. A significant amount of planning goes into a product before anything physical actually exists and it is very important for a user to be identified. I entered this project after the initial idea phase,

therefore the project had a clearly defined direction and purpose so I was able to focus on creating a product which successfully accomplished that purpose.

2. Concept Development

Once the project idea was well defined and the technology behind the project was settled a number of preliminary sketches were drawn up in order to visualize different implementations of the idea. Because this project involves microfluidics, the main focus is controlling the flow of a fluid through minute channels. The concept development consisted of a number of brainstorming sessions in which hundreds of fluid paths were drawn out.

The general concept was defined by the project idea therefore a number of specifications were given prior to designing. The next step was to organize these specifications and come up with a list of ways to make sure each of the specifications were met. A number of preliminary decisions were made early on, which in many ways determined the path of the project. One such decision was the device activation mode. After careful consideration it was determined that manual activation lent itself most to the project. If another method for activation was chosen early on, the end product could be radically different. It was also understood that this step might be revisited depending on the results of other steps of the process.

A two dimensional sketch of the system, consisting of multiple parts was drawn up and then each part was designed separately. It was also decided that O-rings would be used on the device to prevent leaks and ensure that it was hermetically sealed.

3. Computer-Aided Design (CAD)

For this project, the 3D CAD program SolidWorks was used. CAD programs are extremely useful in designing products. By creating a 3D model, SolidWorks allows the user to see exactly what the final product may look like without any manufacturing or fabrication. The SolidWorks computer-aided design software allowed us to turn a 2 dimensional sketch into a 3 dimensional object. Additionally the interface allows quick and easy modifications. The CAD allowed us to work at a very small scale, on the order of microns, which was extremely beneficial to this particular project.

The purpose of this step in the process is to transform the 2 dimensional sketch created in the concept development phase into a 3 dimensional object in CAD. For this device, the project was given a distinct look and in a way became something tangible at this stage in the process. The CAD stage proved to be much more complicated than sketching because of sizing and tolerances. We were limited by the overall size requirement of the device but each part itself had a certain amount of flexibility within the device. The entire device could have a maximum diameter of 20mm and a maximum length of 90mm. During this stage of the development process the exact sizes of parts and how they fit relative to each other was decided. The CAD allowed us to see how our final product would look and make adjustments accordingly.

3.1 O-ring Groove Design

Accommodating the O-rings proved to be a very important aspect of the CAD for this project. Within the device the fluid had to be completely sealed off from the environment until activated therefore we needed to find a reliable seal. It was determined that O-rings would be sufficient. Figure 2 shows how the O-rings are sized.

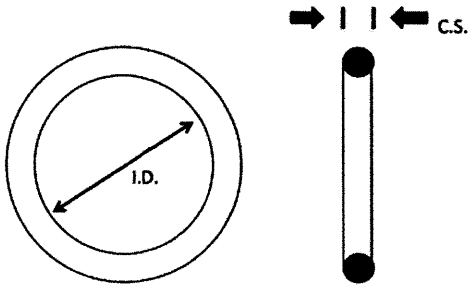

Figure 2. Basic O-ring dimensions are broken into the inner diameter (I.D.) and the cross section (C.S.), which is the diameter of the cross-section.

The size of the device helped to determine which O-rings would work best. An O-ring sizing chart is shown in Table 1.

TABLE 1. The dimensions of all possible O-rings for our device based on size constraint.

Size	I.D. (mm)	C.S. (mm)
-004	1.78±0.13	1.78±0.08
-005	2.57±0.13	1.78±0.08
-006	2.90±0.13	1.78±0.08
-007	3.68±0.13	1.78±0.08
-008	4.47±0.13	1.78±0.08
-009	5.28±0.13	1.78±0.08
-010	6.07±0.13	1.78±0.08
-011	7.65±0.13	1.78±0.08
-012	9.25±0.13	1.78±0.08
-013	10.82±0.13	1.78±0.08
-014	12.42±0.13	1.78±0.08
-015	14.00±0.18	1.78±0.08
-016	15.60±0.23	1.78±0.08

In order to incorporate pre-fabricated O-rings into the design, grooves were created to house the O-rings. The groove design is dependent on the O-ring size chosen. Figure 3 shows the standard groove dimensions used in our design.

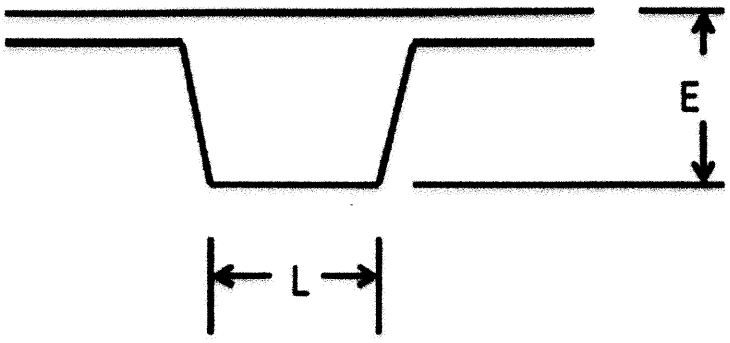

Figure 3. Groove design dimensions where L refers to the seal groove length and E refers to the groove depth.

In designing a microfluidics device, which utilizes, O-rings as a seal it was important to consider the proper dimensions. In this device we wanted to design a gland that was statically secure but also allowed for dynamic motion due to an external force. In order to do this the dimensions were decided on based on an integration of both dynamic and static gland recommendations. The recommended groove dimensions are shown in table 2.

TABLE 3. Accura60 was advantageous because of its durability as well as its clear appearance.

Gland type	O-ring size	O-ring CS (mm)	Gland depth (E) in mm	% Squeeze	Gland width (L) in mm
Static	004 to 050	1.78±0.08	1.270 to 1.321	22 to 32	2.362 to 2.489
Dynamic	004 to 050	1.78±0.08	1.397 to 1.448	15 to 25	2.362 to 2.489

In addition to the dimensions of the actual groove, two other calculations were extremely important when determining the proper sizing of the parts relative to the O-rings. The first is the stretch that the inner diameter of the O-ring is subjected too. This stretch also affects the cross section of the O-ring so it is extremely important to design parts, which place the stretch in the proper range. Stretch is calculated by

$$Stretch = \frac{Groove\ diameter - O\text{-}ring\ I.D.}{O\text{-}ring\ I.D.}$$

In general the stretch should be somewhere between 0-5 %. Excessive stretch may cause the O-ring to degrade faster and may compromise the seal in a product.

Additionally the Squeeze calculation is also very important in order to ensure a proper seal is made between the two corresponding parts. Squeeze is calculated using the formula

$$Squeeze = \frac{O\text{-}ring\ C.S. - Gland\ depth\ (E)}{O\text{-}ring\ C.S.}$$

As shown in table 2 the static glands have a higher squeeze value meaning that the gland depth is smaller, which means that the O-ring is more compressed within the groove. The dynamic glands have more room for the O-ring's cross-section to allow for movement.

When designing a product, which utilizes O-rings, a number of important aspects must be considered. In the overall process of designing a microfluidics device these aspects fell into the CAD step of the process where dimensional decisions and specifications were determined.

3.2 Tolerance

Another important design aspect is tolerance. Regardless of the project type, the issue of tolerance in manufacturing is ever present. When taking this project from concept to 3D design it was very important to have some sense of the tolerance that we were working with. Because of the very small channels this device was intended to have, the accuracy of the design was extremely important. This will become increasingly important in later stages of the device development process but at this point it was assumed that the fabrication mode would be accurate to the thousandth of a millimeter therefore the CAD was designed to reflect that.

4. Simulations

In addition to the 3 dimensional design of the device, the SolidWorks software allowed us to run some basic simulations to see the potential failure points of our device as well as a very basic view of the fluid flow. These simulations were extremely helpful in providing us with a proof of concept.

Computational fluid dynamics (CFD) software, called Flow-3D, was recently purchased to better analyze the fluid flow within the device. The analytic capacity of this CFD software is far superior to the preliminary simulations run on SolidWorks FloXpress. Ideally the CFD simulations would be run prior to the fabrication of the device but because it was not available to us until recently the experimental testing and the simulations are being run in parallel. For future design iterations, the CFD will be done prior to prototyping. The CAD along with the CFD allows us to constantly be designing and simulating in order to find the optimum configuration for fluid flow through our device.

5. Prototyping

Because of the precision and ease of fabrication it was decided that 3D printing was the ideal way to create the prototype. 3D printing is an additive manufacturing process that is both quick and inexpensive. The material and type of 3D printer were extremely important

to the success of the device. A number of different 3D printers were considered but eventually stereolithography (SLA) was decided as the optimal technique.

5.1 SLA

SLA is a 3D printing technique where an ultraviolet light beam is used to build layers of liquid photopolymer resin to create solid parts. A large vat of photo curable resin sits in the printer. A platform is then lowered into the resin while the UV light beam draws the part layer by layer. The size of each layer is determined by the amount the platform descends each time. The layers can be as thin as 0.05mm making the process extremely accurate. Additionally the design is imported from the CAD files making the process relatively simple.

The reason SLA was chosen for the prototyping of this device was mainly based on the high resolution, variety of materials available, and the non-porous texture of the parts. Unlike other additive manufacturing 3D printers, SLA does not lay down layers of plastic in drop form therefore the pieces are completely solid making them ideal for holding fluid. The downside of using SLA technology for rapid prototyping is that it is expensive compared to other types of 3D printing. The resin used to build the parts is very expensive, ranging from $80 to $210 per liter.

The prototype was printed on the 3D Systems ProJet 6000 professional 3D printer. This printer has a maximum build size of 250 x 250 x 250 mm, which more than accommodates the size of our device. Additionally the ProJet 6000 has a build resolution of 25 microns.

5.2 Accura 60 Plastic

Accura 60 Plastic was chosen as the material for our prototype because of its toughness as well as its clear aesthetic. A clear material allows us to observe the flow within the device, which is extremely important for experimental testing. The properties of Accura60 are shown in Table 3.

TABLE 3. Accura60 was advantageous because of its durability as well as its clear appearance.

Property	**SI units**
Tensile Strength	58-68 MPa
Tensile Modulus	2,690-3,100 MPa
Elongation at Break (%)	5 -13 %
Hardness, Shore D	86

6. Assembly

Once the parts have been fabricated and cleaned the device is ready for assembly. In general this is a simple process consisting of adding O-rings and manually fitting parts

together. It is very important for the individuals involved with creating the CAD of the device to be involved in the assembly of the product. When the initial prototype was first received sizing issues were identified during assembly prior to any experimental testing. In rapid prototyping it is expected that the initial models will have tolerance issues. The design changes are then identified and the CAD is modified to reflect these. There must be constant communication between members working on each stage of the process. Issues were addressed and the CAD was modified to better suit the device. We found that for this technology press-fit pieces should have a radial tolerance of about 50 microns. There is a direct feedback loop between the assembly stage and the CAD stage. Our particular product took about 3 physical prototypes until the tolerances were optimized and the device was ready for experimental testing.

7. Conclusions

The final step of the product development process concerns the biochemistry testing of the microfluidics device. This is an extremely important aspect of the project where the success of the project can truly be determined. The scope of this thesis covers the design and prototyping of this device. Biochemistry tests are currently being run on the device and will be crucial on the future design iterations of this device.

Based on the results, the CAD may be modified to improve the fluid flow, or the project may go back to the initial concept development phase and continue through the rest of the process. The point of this paper is to outline the process we took to create a device, primarily focusing on the concept development through the assembly phase. In order to create a successful product the design process may be done several times and the design may go through many iterations. Additionally the feedback gained from the biochemistry testing is extremely important to future design decisions. This is simply an overview of this specific process and the project is far from over. This design process will lead to a better and more successful device in the future.

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