Actuation System for Microfluidic Chips

ECE4011 Senior Design Project

Microfluidic Chip
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Executive Summary

This project focuses on designing and fabricating a microfluidic chip composed of a 12 solenoid microvalve system. The system contains a manifold to interface between the two layers of the microdevice, two pumps and their hardware interfaces, an electronic microprocessor, a software system capable of both manual inspection and automatic sequencing, and possibly external flow and pressure sensors if all other project components are completed within the allotted time period of the senior design class.

The motivation for this project is to assist with the electrical aspects, such as the hardware and software interfaces, of preexisting microfluidic chip designs which will be commissioned for various space exploration and analysis missions, such as the Europan Penetrator mission. [1] Essentially, this mission involved breaking foreign soil on Jupiter's moon Europa and analyzing its contents. The ability to analyze foreign substances could enhance biochemical understanding of reactions that occur under non-earthlike conditions.

The main sources of expenses for this senior design project are the bank of solenoid valves, the two pumps capable of air and liquid flow, and the microcontroller. Some other typical sources of cost that can be omitted by means of employing the school's facilities are the fabrication machines and materials. There is also a significant labor cost. The currently estimated amount of labor hours for this project are currently over 12,000 hours, which could vary depending on any unexpected complications that might arise due to the complexity of this project. The expected outcome is for the team to develop a working microfluidic chip that can functionally interface with multiple external devices, primarily the external solenoid valves and pressure and vacuum pumps. Ideally, the device should demonstrate the ability to mix common assays and to move simple liquids across the device.

1. Actuation System For Microfluidic Chips

Introduction

The microfluidic chip team plans to design and fabricate a microfluidic chip to demonstrate simple mixing and movement of fluids. Our team is requesting $1,730.88 ($2000 to be safe) to design and fabricate a microfluidic chip.

1.1 Objective

The objective is to design and fabricate a microfluidic chip which demonstrates the ability to mix common assays and to move simple liquids across the device. This chip will most likely use a switch-valve system due to their ability to pass liquids bi-directionally, but might include check-valves depending on the final chip design that the group eventually decides upon.

The team plans to control the movement of the liquids on the chip with a pressure generator connected to the pneumatic layer of the chip through a series of solenoids operated by a microcontroller. [2] However, if the team creates a fully functioning microchip controlled by the external components previously mentioned with additional time to spare before the senior design expo, it will also endeavor to create an on-chip microfluidic processor to replace the off-chip microcontroller and pressure generators. [3] This would save space and reduce costs of currently existing microfluidic applications.

1.2 Motivation

Our motivation to develop the microfluidic chip is to provide new technology in the fields of healthcare and environmental engineering. Microfluidic chips can be used to detect concentrations of various substances in the blood (such as glucose and tumor cells), as well as in electrochemistry, micro fuel cells, and chemical microreactors. [4]

1.3 Background

Microfluidic chips manipulate and analyze fluids for a wide variety of applications that suit the needs of chemical and biomedical researchers worldwide. Some examples include chips that analyze Martian soil for the determination of biological content, chips that process blood for detection of cancerous cells, and chips that mix fluids to produce new compounds [2,4]. Further space exploration examples are the Europa Penetrator Probe, as previously described in the executive summary.

2. Project Description and Goals

The current primary project design components include the microfluidic chip to be fabricated, pressure and vacuum pumps, multiple solenoid valves, a microcontroller, and a power source. The microfluidic chip will be fabricated in the Nanotechnology building and will have three layers as described in the design approach section of this proposal. If necessary, all of the components will be purchased from third-party vendors, although if possible components such as the solenoids, pressure and vacuum generators, and power source will be borrowed from Georgia Tech's faculty and facilities.

Project Features:

- Automatic manipulation of the direction of fluidic flow and mixing processes within the fluidic layer of the chip.
- Manual control over the solenoid array to manipulate fluidic flow within the fluidic layer of the chip
- Either pressure sensors within both the fluidic and control layers of the chip to confirm correct microchip operation or a visual display highlighting important features within the chip.

- Possible demonstration of a microfluidic processor analogous to the same microprocessor and solenoid array previously described.

As mentioned in the executive summary, the goal of this project is to create a chip which demonstrates the ability to mix common assays and to move simple liquids across the device. If possible, it will also demonstrate an on-chip processor which achieves the same fluidic control as does the project's off-chip microprossessor and solenoid system.

3. Technical Specifications

The following tables detail the operating parameters for the four primary systems in our design. Table 1 covers the specifications for the microfluidic chip dimensions and its primary material properties. Table 2 displays the solenoid specifications that would be optimal for the scope of this project. Table 3, like table 2, displays the pressure pump and vacuum condition specifications and, finally, table 4 contains microcontroller specifications.

Table 1. Micro-fluidic Chip Dimensions and Properties

Item	Specification
Fluidic Layer	
Dimensions	~ 1cm Thick, ~100mm Diameter
Flow Channels	20-40 um Depth, 40-300 um Width
Manifold Layer	
Dimensions	~ 1cm Thick, ~100mm Diameter
Flow Channels	20-40 um Depth, 40-400 um Width
PDMS Membrane	
Dimensions	254 um Thick
Glass Properties	
Density	2.51 g/cm^3
Strain Point	526 C / 984 F
Annealing Point	557 C / 1035 F
Softening Point	736 C / 1357 F
Hydrolytic Resistance	Class HGB 1

Table 2. Solenoid Specifications	
Item	**Specification**
Style	2-Way Normally Open
Operating Pressure/Vacuum	30 psi Max
Voltage	12/24 VDC
Response Time	5-20 ms
Dimensions	Up to 1.5"x1.5"x3"

Table 3. Pressure/Vacuum Specifications	
Item	**Specification**
Max Pressure Continuous	100 mbar (1.4 psi)
Max Intermittent Pressure	180 mbar (2.6 psi)
Max Vacuum Continous	200 mbar (2.9 psi)
Max Intermittent Vacuum	450 mbar (6.5 psi)
Voltage	12/24 VDC
Dimensions	3" Length, 1.25" Diameter

Table 4. Micro Controller	
Item	**Specification**
Channels	>16
Measurement Type	Digital I/O
Interface	USB

4. Design Approach and Details

4.1 Design Approach

To recap, our current objective is to utilize and also extend the current interfacing equipment for a twelve-valve microfluidic system in order to achieve a precise set of mixing operations. Each switch valve on the chip turns on or off, opens or closes, based on a pressure controlled input. A switch valve is considered open when the input pressure is low. Likewise a switch valve is considered closed when its input pressure is high. [5] The input pressure to each of the valves is obtained by a plastic tubing which is connected to an off chip pressure generator. The pressure generator is a single unit which consists of multiple pressure lines. For our chip, if we consider that each valve was operated separately from each other valve, we would require a pressure generator with at least twelve different lines, each of these connected via a plastic tube to a solenoid valve. Each valve would be controlled from inputs sent from a microcontroller, commanding whether to be open or closed, thus controlling whether the switch valves on the control layer of the chip are operating in an open or closed sate. [6] By changing the pressures in the valves, fluid can be caused to move from port to port within the fluidic layer of the microchip.

Each particular state of the system can be represented by a twelve-bit binary number in which “1” represents high pressure to a valve and “0” represents low pressure to a valve. In this way, it is possible to describe an entire series of actuations for all twelve valves by creating a list of these twelve-bit binary numbers, with each bit in the number being associated with a particular switch valve {100100001100, 10011000101….,11000010110 From a top level view this amount of information is sufficient to describe the functioning of the chip. More technical details describing the three-layer chip are explained later in the section.

Figure 1 summarizes the operation of the system. A pressure generator receives a signal from a microcontroller to turn on or off. The pressure generator should have connectors which can accommodate the solenoid array. Each output line of the pressure generator can be connected to a solenoid. [3] Each solenoid will have a line connected to an output pin of the assigned microcontroller. Additionally, each solenoid will also have an outgoing tube connected to it that interfaces directly with the valves on the chip. Voltage signals may be sent to from the microcontroller via the lines which connect it to the solenoid array in such a way that each solenoid becomes either a source of high or low pressure. The high pressure is generally indicated by water that is pumped through the plastic tubes connected to each solenoid while low pressure is indicated by air.

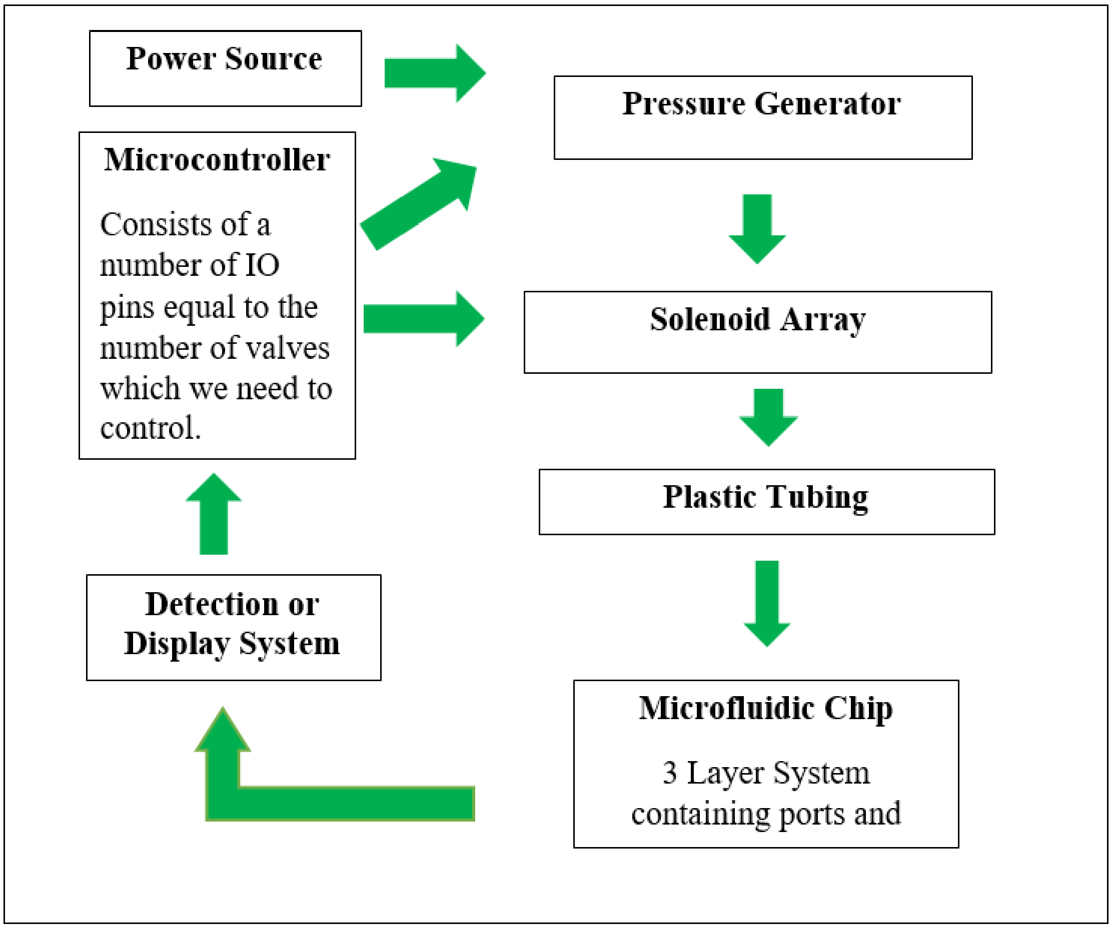

Figure 1. Block diagram schematic showing the overall schematic of the microfluidic system. In the case of the purely on-chip microfluidic controller, all of the off-chip components would be removed, leaving only the microfluidic chip and any additional detection systems that might be deemed necessary to display the movement of fluids within the chip.

The three-layer chip, controlled by the pressure generator and solenoid array, is composed of a fluidic layer, a control layer, and a PDMS layer, shown in figure 2. [2] The fluidic layer, which is normally situated on top of the PDMS and control layers, houses the liquid whose movements are the subject of manipulation dictated by the microcontroller. This layer contains channels for the passage of liquid and it contains the top half the switch-valves necessary to facilitate fluidic movement within the chip. The control layer, normally situated beneath the fluidic and PDMS layers, is attached to the solenoid array and houses the bottom half of the switch-valves as well as channels providing the input pressures dictating whether the switch-valves are considered open or closed. The PDMS layer is necessary to separate the two halves and provide a flexible medium to act as the gate which prohibits the flow of liquid in the liquid layer depending on the pressure levels of the channels in the control layer. Figure 3 displays a switch valve design, as well as a check valve design, that will be used in the project. [3]

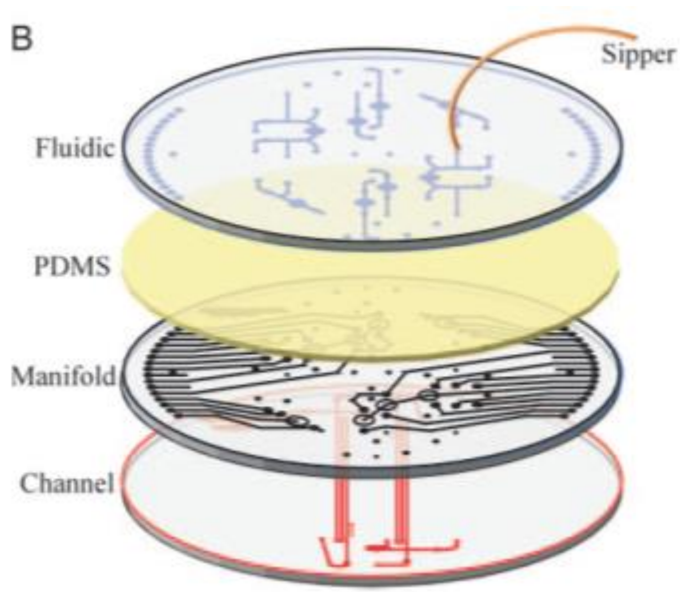

Figure 2. Shown is the three-layer chip design. Primarily, the chip will consist of a fluidic layer, a PDMS layer, and a control, or manifold, layer. Additional layers, as shown above, can be added to improve the functionality of the chip design.

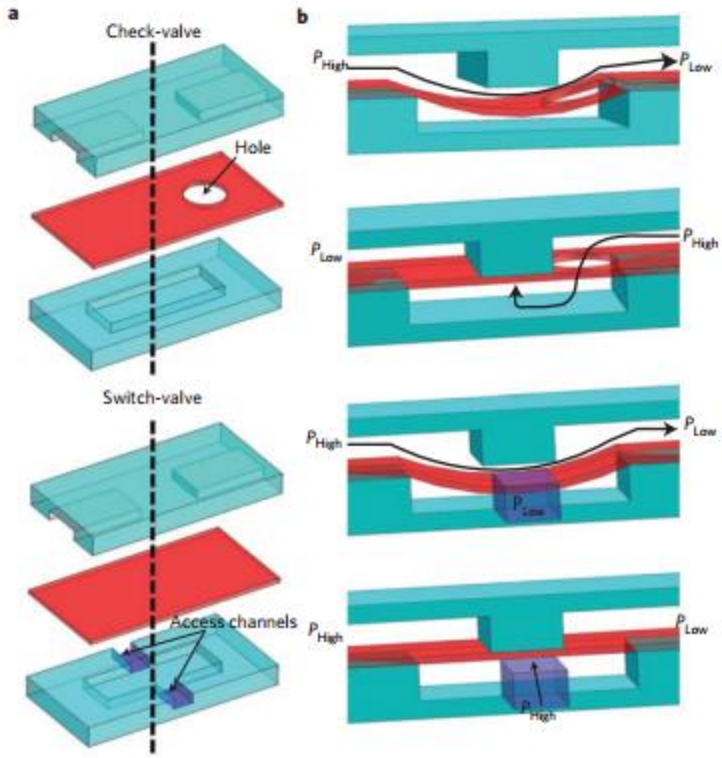

Figure 3. The left image shows a top down view of both a check-valve, top, and switch-valve, bottom. The right image displays the same valves, but from a side view.

4.2 Codes and Standards

In terms of the technical specifications for the pressure generators, or vaccumes, operating on microchips of the style that the group plans to build, the maximum pressure that should be safely implemented is no more than 7 psi [7, 8]. Additionally, the components that are interfacing with the power supply often use between 12 to 24 volts.In terms of software programs, National Instruments' LabView is a common program development environment and will be used to synchronize the IO components of the project. Other types of interfacing software will have to conform the ASCII C/C++ standards. [9] Finally, in terms of the fabrication process, proper laboratory safety procedures will be followed and any harmful by-products will be properly contained and disposed of.

4.3 Constraints, Alternatives, and Tradeoffs

The current approach for controlling mixing of fluids in valves and ports is not necessarily the most ideal because of the large amount of off chip interfacing equipment that is required. In fact the team's initial design approach was to eliminate all of the off chip components and instead have the chip function as a fully self-regulated system. There have been a few significant papers in this direction, most notably the work by Takayama et al on the design and fabrication of microfluidic oscillator circuits [6]. The team's plan was to build a microfluidic oscillator circuit which would be fabricated in the same process as the 12 port system. The oscillator circuit would be given a single fluidic input and consequently by nature of its design would act to move fluids in and out of the various ports of the 12 port system in a precise manner. Although the team made significant efforts to move in this direction the fabrication process proved to be too complicated to be created within the limited scope of the second senior design semester. Also, due to the nature of the senior design project, it was in the team's best interest to make our innovations in the interfacing aspect of the design as opposed to the fabrication aspect because of the ECE requirement of focusing heavily on electrical hardware.

Additionally, although the on-chip fluidic controller system was the alternative that we pursued the most, there were systems which had entirely different physical architectures than the pneumatically driven valves. One such example was the approach of electro-wetting on a dielectric (EWOD). [10] This approach involved fabricating a microelectrode array where each electrode may be set to a particular voltage. Fluid droplets are placed on the array and by changing to voltage at each electrode it is possible to move the fluid around the chip as a discrete droplet. However the only drawback is that this approach drains a lot of power because voltage is directly proportional to power. At present, the team is continuing with a pneumatically actuated control system. The primary constraints to this system would be off chip complexity. While not really a limitation for the senior design expo, this might significantly alter the commercial viability of the designed system.

5. Schedule, Tasks, and Milestones

The team will design and prototype this actuation system for microfluidic chips during the Fall 2016 and Spring 2017 semester. There will be hardware and software components to this project. Both components' task breakdowns, milestones, timeline, start date, end date and duration are shown in the Gantt Chart in Appendix A. Appendix B contains a list of milestones, difficulty and risk levels, and person assigned to each respective task. Appendix C proves a comprehensive PERT chart also including task breakdowns, milestones, timeline, and more.

6. Project Demonstration

The demonstration of the prototype will take place at the Georgia Tech Design expo. There will be two main methods by which the prototype will be demonstrated: Manual and Automatic.

6.1 Manual Manipulation of Microvalves

The first part of the project demo will be to show off the user-programmed control of the microvalves for manual testing and inspection. Ideally, the user will be able to manually open and close the solenoids which release the liquids through the valves for either movement or mixing. The software interface to manually control the microfluidic chip through the microcontroller will either be run through a proprietary software, such as LabView or Matlab, or through a program constructed by the team. Programming an original software is a challenge that will be considered with the proprietary software as a fallback if the software created by the team fails to work.

6.2 Automated sequential mixing

The second part of the demonstration will to show how the software interface can be automated to pass and mix assays through a repeating sequence that will be determined by the user. This will be done using the same software that ran the first part of the demo.

7. Marketing and Cost Analysis

7.1 Marketing Analysis

The field of microfluidics is growing exponentially, but hardware actuation systems for microfluidic chips are still in the developmental phase of a very niche market. The target market for this actuation system is currently limited to institutions and high-level research companies due to its cost and application specific development for a variety of applications including, but not limited to, biomarker detection, DNA detection, water purity, and blood concentration. The actuation control system market product could potentially expand to other sectors, but most likely not in the next few years.

Since Quake's introduced large-scale microfluidic chip integration, chemists and biologists rushed to development of these systems for analysis. Jungkyu Kim, Amanda Stockton and many other professors at various universities around the US have developed programmable microfluidic platforms. [6]. Other groups have also developed automated microfluidic platform for synthetic biology and analyzing DNA. [4]. However, all these systems focus more on analyzing and processing the fluids.

Our proposed system focuses on the controls side of the microfluidic chip, creating a simple microfluidic mixing system including hardware components and software components. While traditional projects in this field have been developed and utilized for detecting biomarkers and amino acids on Mars [1], this system places an emphasis on simplifying the control of different fluids in and out the chip as well as processing the liquids on the chip.

7.2 Cost Analysis

The development cost for the microfluidic actuation system is approximately $1730.88. Table 1 shows the breakdown of the material costs for the entire system. The solenoid valves are the most expensive especially with the number that is needed to control each valve. Some of these products are available in the advisor's lab and may be used to reduce costs; however it is not guaranteed that the products are available at the team's disposal. The final product will need all these components and could require less valves depending on the scale of chip created.

Product	Quantity	Unit Price ($)	Total Price ($)
Microchip	1	$150	$150
Solenoid Valves	12	$69.99	$839.88
Tubing	2	$6	$12
Pressure Pumps	2	$300	$600
Power Supply	1	$40	$40
Microcontroller	1	$89	$89
Total Equipment Costs			$1730.88

Table 5. Estimated material costs of the senior design project

The total development costs show in table 6 assumed labor cost of $45 per hour for a typical entry-level electrical engineer. Fringe benefits, overhead costs, and sales expenses are factored into the calculations for setting the pricing of this system where it will be amortized over all units produced. Tasks such as software coding, integration of the chip and external components, as well as debugging and controlling the movement of fluids will have high labor hours and result in high costs due to the many variables of failure and complexity of design.

Component	Labor Hours	Labor Cost	Part Cost	Total Component Costs
Microfluidic Chip				
Mask Design	56	$2520		$2420
Fabrication	80	$3600	$150	$3750
External Components				
Integration with Chip	200	$9000	$1580. 86	$10580.86
Software				
Design	180	$8100	$89	$8189
Code Debugging	100	$4500		$4500
Software and Hardware Compatibility	150	$6750		$6750
Demo Preparation	200	$9000		$9000
Group Meetings	300	$13500		$13500
Total Labor Cost		$56970		$56970
Total Part Cost			$1819.86	$1819.86
Total Cost (Labor + Part)				$58789.86

Table 6. Developmental costs of the senior design project

The total development cost for the microfluidic actuation system is $166,937.89 assuming the fringe benefit as 30% of total labor and overhead as 120% of material and labor show in table 7.

Parts	$1819.86
Labor	$56970
Fringe Benefits (% of Labor)	$17091
Subtotal	$75880.86
Overhead (% of materials, labor, and fringe)	$91057.03
Total	$166937.89

Table 7. Developmental costs of senior design project including Fringe Benefits and Overhead.

The production will consist of 10 units sold over a 5-year period at a price of $6000 per unit. Due to the price and capability of the device, only a maximum of 2 units per year will be sold. Intellectual property contracts may be conducted based on the novelty of this system. Each unit for a complete system requires all the material components resulting a total cost of $1819.86. A team of skilled engineers will be employed at $40 an hour to fabricate the chip, interface the external controls of the system and integrate the hardware with the software components. Sales will be very low about 2% of the selling price at $100 because this is a specialized and powerful device, consisting of pitching the system to large companies and research institutions. At $6000 per system, the expected revenue is $60000 yielding a profit of $924.71. Production costs, profit, sales, amortized development costs, and selling price is show in table 8.

Parts	**$1819.86**
Assembly Labor	**$40**
Testing Labor	**$20**
Fringe Benefits (% of Labor)	$18
Subtotal	$1897.86
Overhead (% of materials, labor, and fringe)	$2277.432
Subtotal, Input Costs	$4175.292
Sales Expense	$100
Amortized Development Costs	$800
Subtotal, All Costs	$5075.29
Profit	$924.71
Selling Price	$6000

Table 8. Production costs, developmental costs, selling price, and profit projections for each unit sold.

8. Current Status

Currently, due to several changes in direction throughout the design process as well as scheduling issues, the team has only been able to draft a simpler version of the final prototype that only passes through a liquid through two directly connected chambers. Soon, after this design has been tested and it is proven that a liquid can be passed through two chambers, the team hopes to scale the device up step by step until the final design is fabricated which achieves the original project goal of demonstrating the ability to mix common assays and to move simple liquids across the device.

9. References

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[10] J. Lee and C.-J. Kim, "Surface-tension-driven microactuation based on continuous electrowetting," Journal of Microelectromechanical Systems, vol. 9, no. 2, pp. 171–180, Jun. 2000.

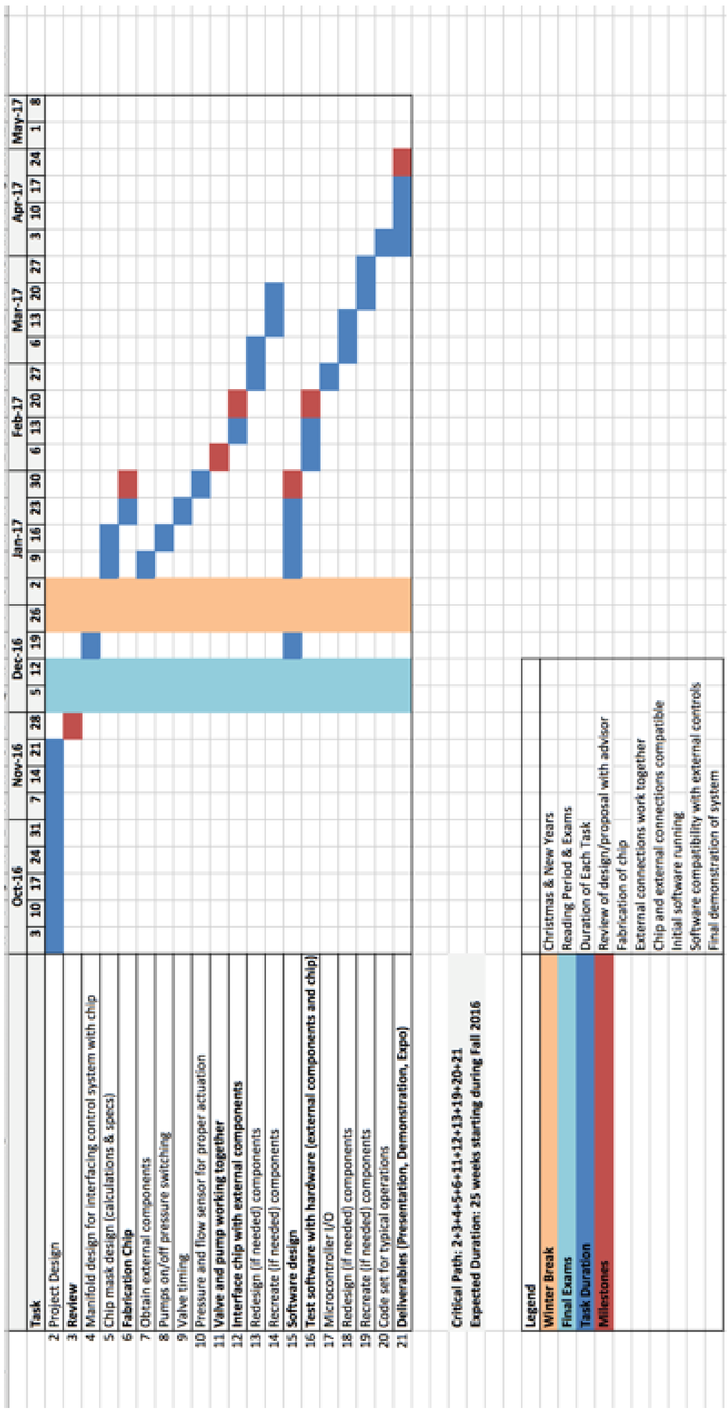
Appendix A

List of Gantt Chart Tasks

	Task	Start Date	End Date	Weeks
2	Project Design	3-Oct	27-Nov	8
3	**Review**	**28-Nov**	**4-Dec**	**1**
4	Manifold design for interfacing control system with chip	19-Dec	8-Jan	2
5	Chip mask design (calculations & specs)	9-Jan	22-Jan	2
6	**Fabrication Chip**	**23-Jan**	**5-Feb**	**2**
7	Obtain external components	9-Jan	15-Jan	1
8	Pumps on/off pressure switching	16-Jan	22-Jan	1
9	Valve timing	23-Jan	29-Jan	1
10	Pressure and flow sensor for proper actuation	30-Jan	5-Feb	1
11	**Valve and pump working together**	**6-Feb**	**12-Feb**	**1**
12	**Interface chip with external components**	**13-Feb**	**26-Feb**	**2**
13	Debugging	27-Feb	12-Mar	2
14	Fix errors	13-Mar	26-Mar	2
15	**Software design**	**19-Dec**	**5-Feb**	**5**
16	**Test software with hardware (external components and chip)**	**6-Feb**	**26-Feb**	**3**
17	Microcontroller I/O	27-Feb	5-Mar	1
18	Debugging	6-Mar	19-Mar	2
19	Fix errors	20-Mar	2-Apr	2
20	Code set for typical operations	3-Apr	16-Apr	2
21	**Deliverables (Presentation, Demonstration, Expo)**	**16-Apr**	**23-Apr**	**2**
22				
23	Software Sub-Team			
24	Hardware Sub-Team			

Appendix B

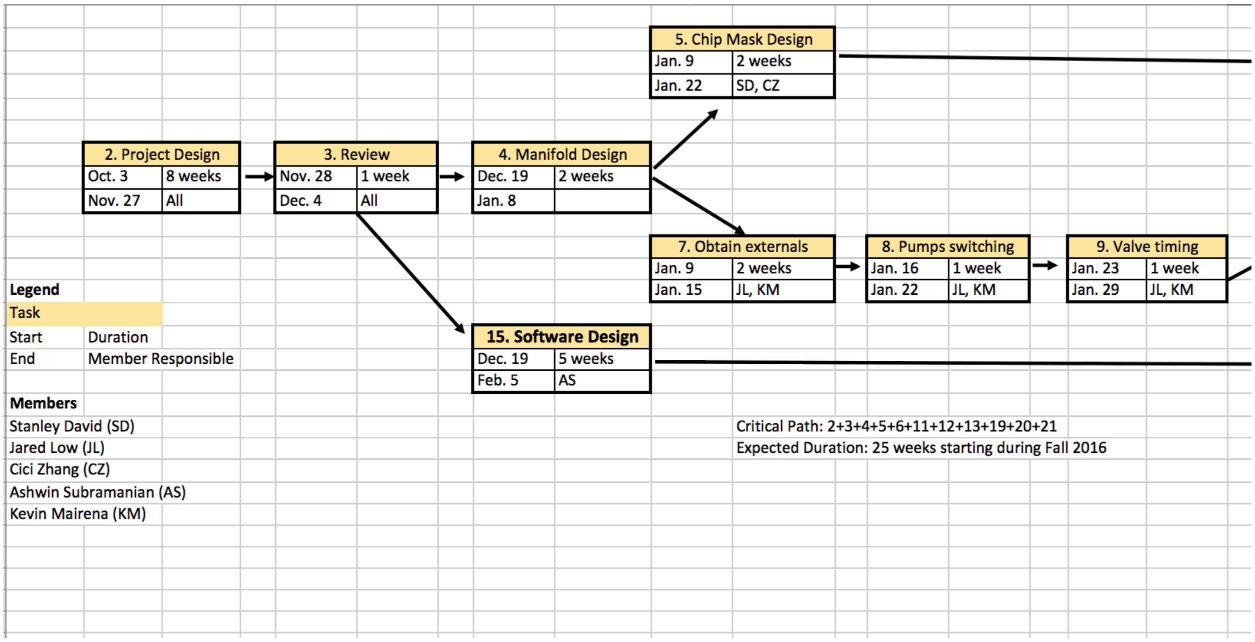
Comprehensive Gantt Chart



Task Name	Task Lead	Difficulty Level	Risk Level
Planning and Documentation	**All**	**Medium**	**Low**
Technical Review Paper	**All**	**Low**	**Low**
Project Summary	**All**	**Low**	**Low**
Project Proposal	**All**	**Medium**	**Low**
Final Project Presentation	**All**	**Medium**	**Low**
Final Project Demonstration	**All**	**High**	**Medium**
Final Project Report	**All**	**Medium**	**Low**
Microfluidic Chip Design	**SD, CZ**	**High**	**High**
Chip Mask	**SD, CZ**	**Medium**	**Low**
Manifold interfacing control system and device	**SD, CZ**	**High**	**High**
Fabrication	**SD, CZ**	**High**	**High**
Testing Chip	**SD, CZ**	**Medium**	**Medium**
External Chip System	**JL**	**Medium**	**Medium**
Pumps on/off pressure switching of 2 pumps	**JL, KM**	**Medium**	**High**
Valves ms timing of switching solenoids	**JL**	**Medium**	**Medium**
Valves and pumps working together	**JL**	**High**	**High**
Software	**AS**	**Medium**	**Medium**
User-programmed pre-timed sequencing of valves	**AS**	**Medium**	**Medium**
Code set for typical operations	**AS**	**Medium**	**Medium**
Microcontroller I/O	**AS, SD**	**Low**	**Medium**
Detection	**KM**	**High**	**High**
Pressure sensor of proper actuation	**KM**	**High**	**High**
Flow sensor of proper actuation	**KM**	**High**	**High**
Improvements	**All**	**High**	**High**
Contingency Planning	**All**	**Medium**	**High**

Appendix C

PERT Chart



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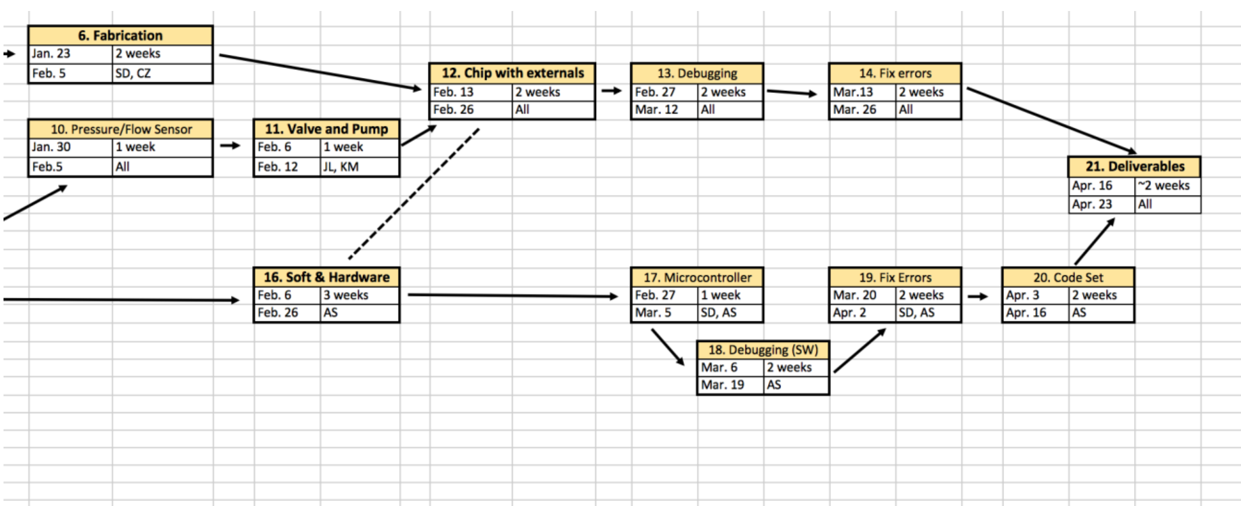

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