

Systems-Level Modeling of Particle Steering using Microfluidic Device

ENES489P: Hands-On Systems Engineering Project Report

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PROJECT ABSTRACT:

Systems engineering is an effective tool in modeling many different types of processes. It can be used to simplify complex biological systems, for example, by defining their sub-systems, requirements, constraints, and the relationship between them. In the following report, a systems-level approach is used to analyze a microfluidic particle steering device. The device functions by sensing the position of a fluorescently tagged particle within a microfluidic channel and comparing it to a desired location that is entered by the researcher. This information is analyzed by a control algorithm that processes the error between the current and wanted position of the particle. Then a computer sends output to a steering mechanism that will guide the particles to the proper location. This process is repeated until the particle has been steered along an entire path.

The structure of the device consists of the particles, steering mechanism, optical sensor, control algorithm, computer, fluid, and channel. Different options for these components are considered in order to optimize the device's function. Specifically, the steering mechanism used, accuracy, and speed of the system are broken down into their low-level requirements and constraints. Constraints and requirements are then subjected to a trade-off analysis in order to determine the optimal combination of components for the researcher's purposes.

TABLE OF CONTENTS:

Project description	1
Problem Statement	1
Customer Requirements	1
Objectives	1
Terminology	1
System structure	3
Structure diagram	3
Structure Description	3
Relationship between Components	5
System Behavior and Use Cases	7
Activity Diagram	7
Use Case Diagram	8
Textual Scenarios	8
Sequence Diagram for Use Case 1	12
Requirements and Traceability	16
Traceability Matrix from Requirements to Use Cases	17
Specifications	18
Requirement Diagrams	19
Traceability of Design Options to System Level Requirements	22
Trade-Off Analysis	24
Pareto Analysis	29
Validation and Verification	30
References	32

PROJECT DESCRIPTION

Problem Statement

The steering of particles, especially cells, is fundamental to the advancement of the medical field. It is a small, yet important component of diagnostic and therapeutic medicine. Therefore, the optimization of the process could have a lasting impact on research and health care. Scientists and engineers interested in microfluidic devices currently spend time and resources on extraneous tasks such as trial and error in order to improve existing models. With the help of a systems model, possible outcomes can be predicted before the fabrication of a device.

Important factors that will drive the economics of the development are the accuracy of the actuators, optical sensors, and feedback control system. Generally, the more efficient these components are, the pricier they become. Therefore, the aim of this analysis is to determine the best possible compromise between cost and efficiency.

Customer Requirements

The customer requires that the device be able to steer a particle along a desired path within a microfluidic channel using any type of actuators. The task of steering one particle must be completed within a few seconds. In addition, the project must fall within a reasonable budget.

Objectives

The purpose of this report is to demonstrate the extent to which high-level systems concept SysML software can be used to describe the functionality of this system. This study lays out a framework for a new system to be developed in order to satisfy the customer's requirements. The following issues, which are useful in performing a detailed analysis of the system, will be addressed in this study:

1. What should the system do?
2. What are the systems requirements?
3. How does the system work?
4. Can the system work?
5. What objects should be chosen and each of the subsystems functionality?
6. How should the object/subsystem interact?
7. How to verify and validate the system?

Terminology

- **Steering Mechanism:** The steering mechanism will involve the actuators involved in controlling the movement of the fluid and/or particles. It will consist of mechanical components that either creates an electric or magnetic field, to which the particles respond to.

- **Optical Sensor:** The optical sensor is part of the feedback control loop. It determines the location of the particle and transmits this data to the control algorithm.
- **Control Algorithm:** The control algorithm is a set of code that is able to process the data received from the optical sensors and determine the next step necessary.
- **Particles:** The particles will be the objects steered in the system.
- **Ferro-magnetic Particles:** The ferro-magnetic particles will be required when using magnets as the steering mechanism. They will be coupled with the particles used in the system and allow for the creation of a magnetic field.
- **Fluid Flow:** The fluid flow can affect the steering capabilities of the steering mechanism. Some of the fluid properties that play an important role are:
 - **Laminar Flow:** Laminar flow is critical in avoiding disruption of the particle paths.
 - **Viscosity:** The viscosity will affect the steering ability of the actuators. The higher the viscosity, the more power and force is required to move the particle within the fluid. It also increases the time it takes to fully steer the particle. A low viscosity fluid, however, may cause the steering to become more unpredictable and less accurate

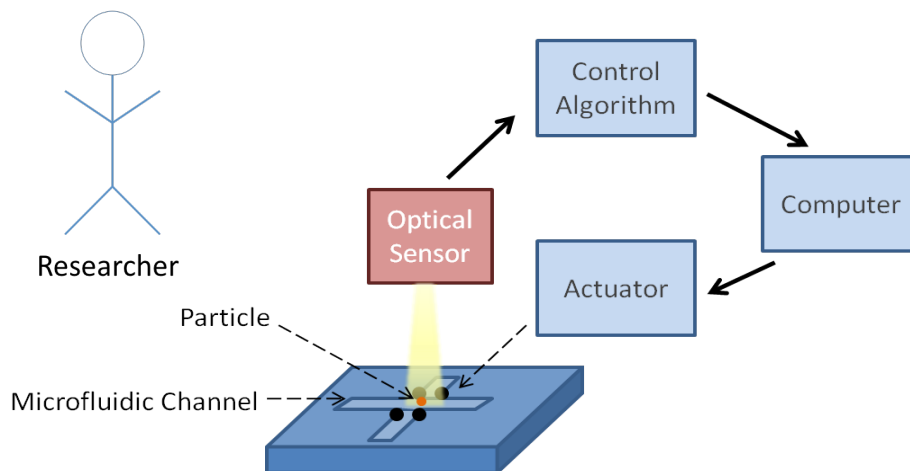


Figure 1 - Simplified flowchart of the microfluidic device. It shows the particle (orange) within the microfluidic channel. The optical sensor picks up its location, sends this data to the control algorithm within the computer where it is processed. Lastly, the computer transfers commands to the actuators, which can then change the position of the particle. This process continues to loop until the particle has followed the desired path.

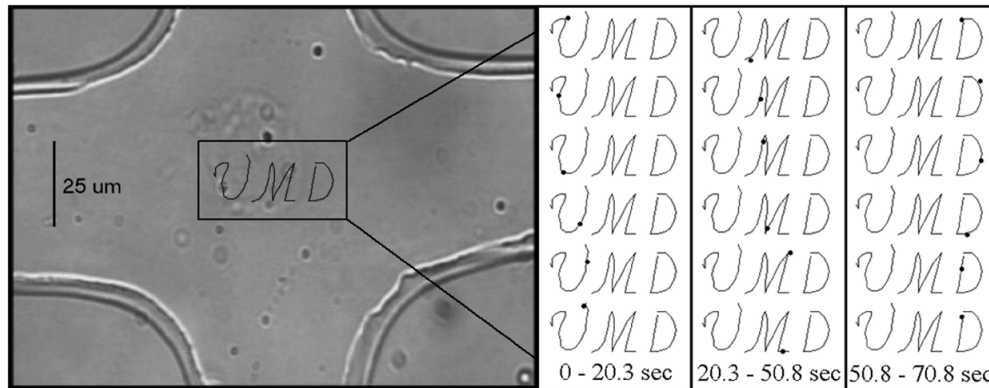


Figure 2 – Picture showing the overall scope of the final product. Channel and electrodes arranged in a cross formation are shown at the left along with the entered path that the particles follow. Particle position and time are shown on the right of the diagram. These reflect the final function and performance of the system.

SYSTEM STRUCTURE

Structure diagram

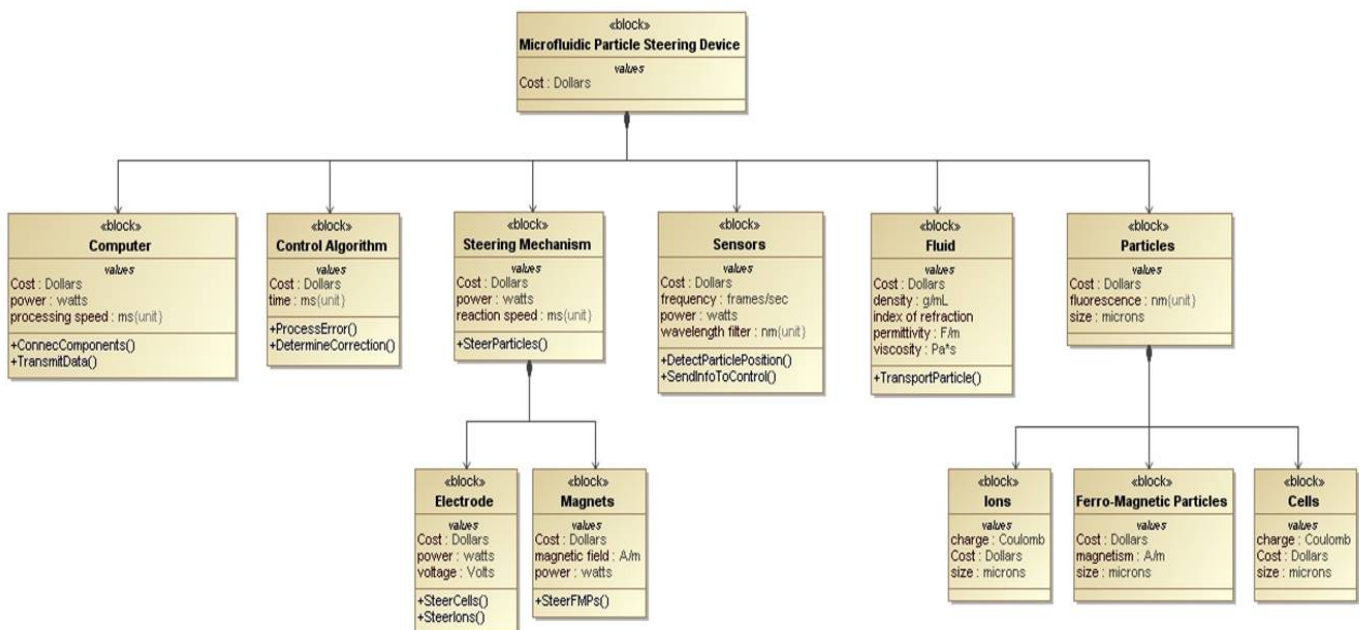


Figure 3 – Structure diagram for the overall system

Structure Description

Microfluidic Particle Steering Device:

The device will allow the user to steer certain particles along a desired path. The system will be contained in a channel of given dimensions. Important components will include a

steering mechanism, the appropriate particle and fluid types, an optical sensor, processing component, and a control mechanism. The process begins when the particles and fluid are placed into the channel. Next, the optical sensor is able to determine a specific particle's location and pass this information on to the computer for processing. The control algorithm then determines the appropriate action necessary to maintain the particle on the inputted path. The steering mechanism translates this data into an output, which affects the fluid, and in turn the movement of the particle. The process then begins again, starting with the sensing of the particle's location.

Steering Mechanism:

An important component of the system is a steering mechanism. The steering mechanism acts to control the fluid in order to guide the particles along the desired path. The steering mechanism receives signals from the processing component and activates at the appropriate time in order to direct particles in the proper direction. Depending on the the specific particles and goal of the researcher different steering mechanisms can be chosen. These are discussed in further detail within the use cases.

Particles:

One of the primary actors of the system are the particles, which are the entities actually being steered in the device. The particles are initially chosen by the researcher and placed in the channel, beyond which point they are controlled by the steering mechanism and fluid in the channel. In order for the particles to be tracked by the optical sensor, they will all be fluorescently tagged with proteins such as green fluorescent protein (GFP). An important consideration for the device is the relationship between certain types of particles, fluid types , and steering mechanisms, which will be discussed later.

Fluid:

The fluid will contain a given particle type and can react to certain outputs of the steering mechanism. Fluid properties such as viscosity, the Reynolds number, and optical properties can affect the response of the fluid to the stimulus of the steering mechanism. In some cases, the fluid may act as the communicator between the steering mechanism and the particle because the mechanism acts directly on the fluid, which then carries the particle. In other cases, the fluid may simply be the medium in which the particles are held, but the steering mechanism acts on the particles, rather than the fluid.

Control Algorithm:

The control algorithm is the software component that analyzes and processes the input data from the optical sensors. Based on a given margin of error, it is able to determine the next move necessary to maintain the particle on the wanted path using a set of code. For example, if the particle has veered a few microns to the left, but is meant to go straight, the control algorithm

will calculate the actuator's output necessary to push the particle or fluid to the right to get back on track. When the particle is already on the set path, the control algorithm will not output any actions to the actuators, such that the particle will remain on its current trajectory.

Computer:

The computer is the hardware component of the microfluidic steering device and acts as the physical connection between the optical sensors, control algorithm, and the steering mechanism. It receives information from the optical sensors, analyzes, and computes data using the control algorithm, and then sends an output to the actuators, which in this case is the steering mechanism.

Sensors:

The optical sensor uses a laser to sense and determine the location of the particle within the channel. It sends the XY-position of the particle to the computer, which then uses the information to decide the response of the actuators. All particles will be fluorescently tagged, allowing the optical sensor to detect them within the fluid. The sensor functions under a boolean expression, which means that it only detects whether a particle is present or not, but not its velocity, acceleration, or other properties.

Relationship between Components

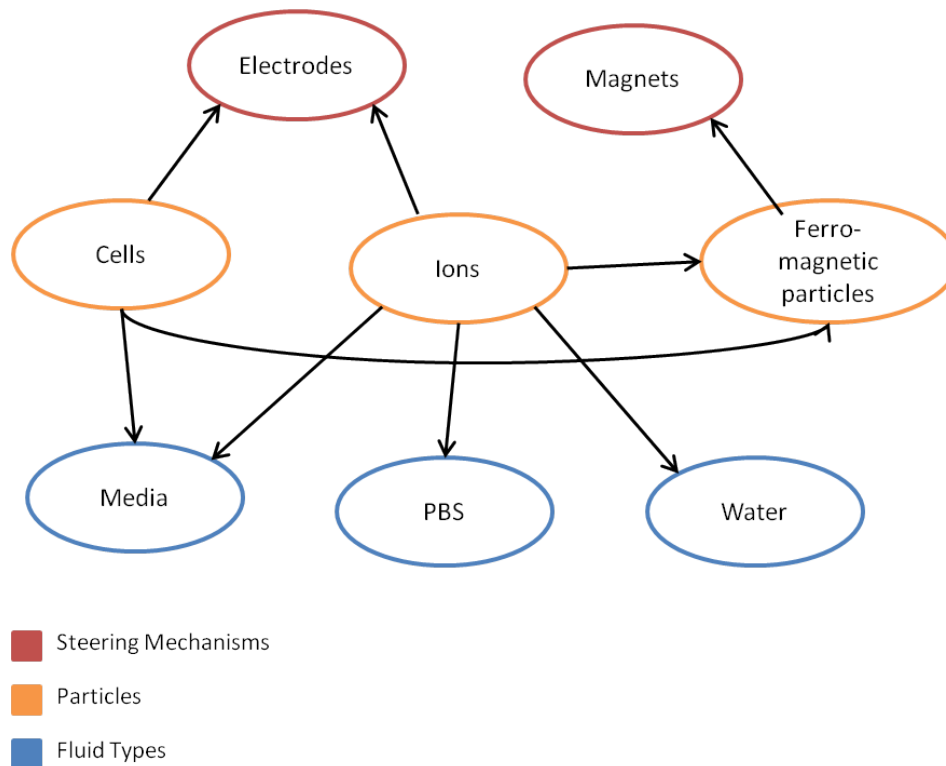


Figure 4 – Diagram showing relationship between certain components of the system

The diagram above outlines the relationships between certain components of the system. Due to the biology of the system certain components will only function with a specific set of other components.

Two particle types are considered for this device: cells and ions. Cells and ions can both be steered by electrodes because the electrodes function by altering the fluid flow rather than directly interacting with the particles. Neither cells nor ions can be controlled by magnets alone because the magnets must act on a magnetic particle and do not alter the flow within the channel. In order to control cells and ions with magnets, they must be coupled to a ferro-magnetic particle.

The particles in part dictate the steering mechanism used but also the fluid type within the channel. Cells have nutrient needs that must be met by the system; therefore they can only be used in a cell culture media that will allow the cells to live during the tests. Ions are dielectric particles that do not have any inherent nutrient needs like cells do. They can be placed in any of the fluid types (which are chosen depending upon the researcher's needs) and be reliably steered.

The fluid types are not directly related to the steering mechanism. All the fluid types are water based and both steering mechanisms can function by the same principles regardless of what fluid type is being used within the channel.

Activity Diagram

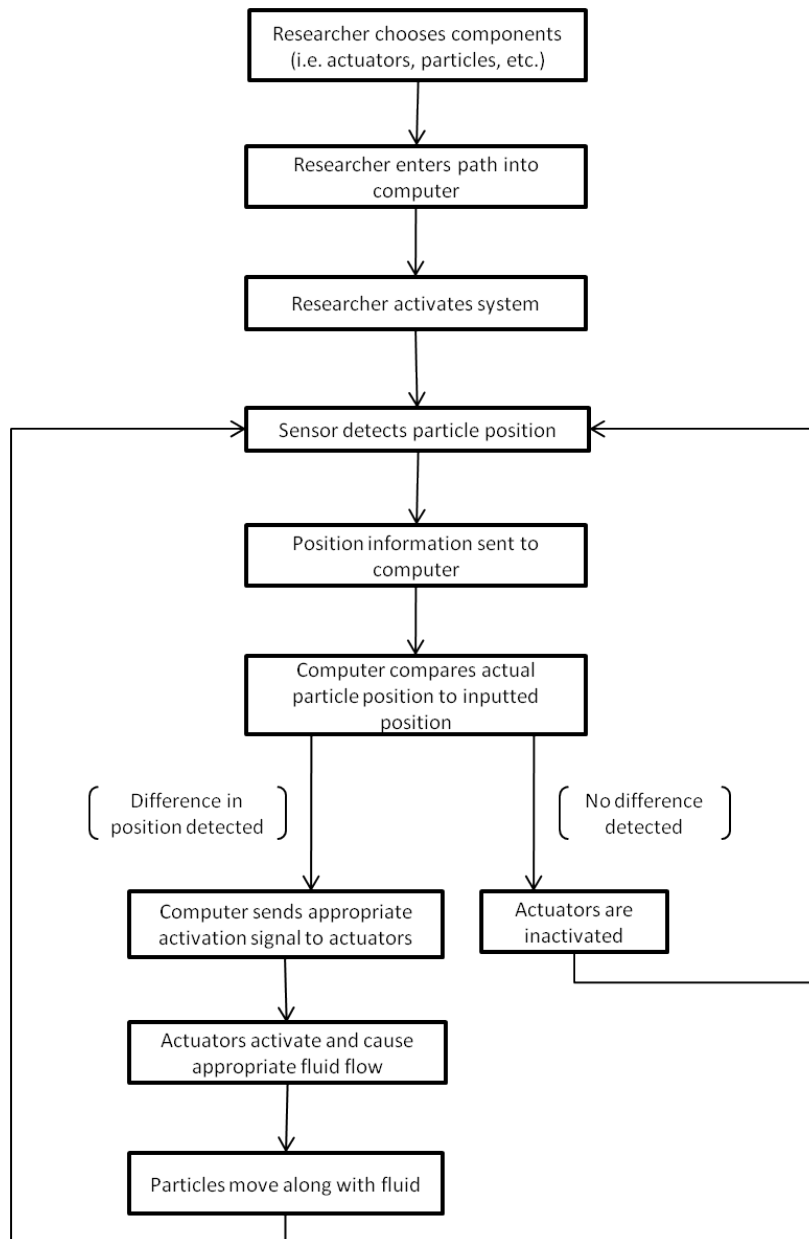


Figure 5 - Activity diagram for overall system process

Use Case Diagram

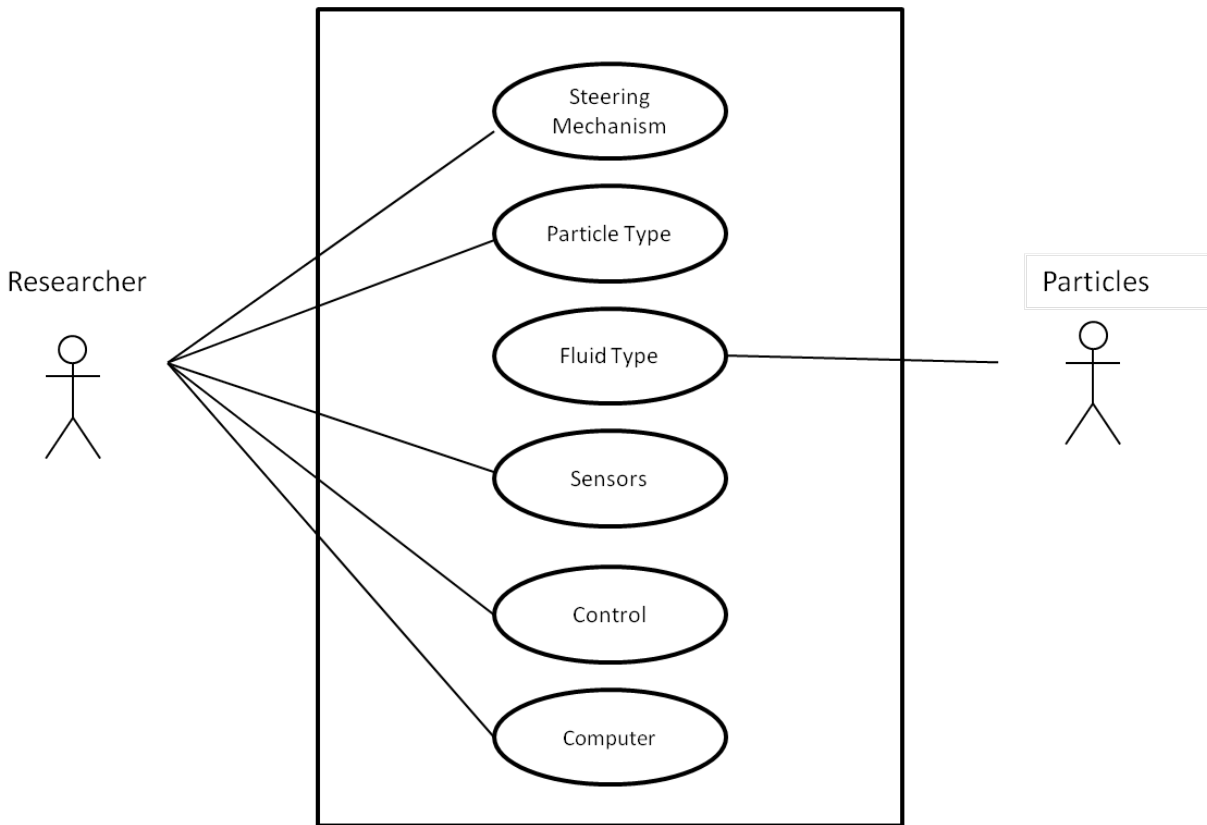


Figure 6 - Use case diagram

Textural Scenarios

Use Case 1: Particle Steering

The first use case addresses the researchers desire to steer a particle along a specific path. Based on the biology of the system being studied, different approaches are possible which will allow the researcher to steer particles but the general behavior of the system remains the same: The researcher enters the desired path into a computer, a sensor will then determine the position of the particle, that information is sent to the computer which computes error between the position of the particle and the entered path, the computer sends an output to actuators that create a specific fluid flow that carries particles to their proper position based on the user-entered path.

This process is continually repeated. Based on the system being studied, the researcher will choose components most suitable to their specific application. Possible scenarios are listed below:

Scenario (1.1): Electrode Steering on Particles

Description: Electrodes creates charged field which directs particles in desired direction.

Primary Actors: Particles

Primary Objects: Electrodes

Pre-conditions: The fluid reacts as predicted in response to the electrode stimulus. Also, particles do not interact with surrounding channel other than in response to changes in the charge. Channel geometries are known and cannot interfere with particle steering.

Flow of events:

1. Desired path is entered by researcher
2. Particles are introduced to system
3. Sensor senses particles position
4. Computer analyzes path based on inputted path
5. Control algorithm activates electrodes based on computer analysis
6. Electrodes activate, creating flow and steering particle
7. Sensor senses position and the process loops

Post-conditions: Reaction of charged particles known, particles can be steered reliably along a path.

Scenario (1.1.1): Cells used with Electrodes

Description: Cells will be steered by electrodes through a desired path

Primary Objects: Cells and electrodes

Pre-conditions: The cells within the fluid react as predicted in response to the electrode stimulus. Also, cells do not interact with surrounding channel other than in response to changes in the charge. Channel geometries are known and cannot interfere with particle steering.

Flow of events:

1. Desired path is entered by researcher
2. Cells are introduced to system
3. Sensor senses cells position
4. Computer analyzes path based on inputted path
5. Control algorithm activates electrodes based on computer analysis
6. Electrodes activate, creating flow and steering cells
7. Sensor senses position and the process loops

Post-conditions: Path of the cells is known and can be reliably steered.

Scenario (1.1.2): Charged Ions used with Electrodes

Description: Charged Ions will be steered by electrodes through a desired path

Primary Objects: Charged ions and electrodes

Pre-conditions: The charged ions within the neutral fluid react as predicted in response to the electrode stimulus. Also, ions do not interact with surrounding channel other than in response to changes in the charge. Channel geometries are known and cannot interfere with particle steering.

Flow of events: Desired path is entered by researcher

1. Charged ions are introduced to system
2. Sensor senses cells position
3. Computer analyzes path based on inputted path
4. Control algorithm activates electrodes based on computer analysis
5. Electrodes activate, creating flow and steering cells
6. Sensor senses position and the process loops

Post-conditions: Path of the cells is known and can be reliably steered.

Scenario (1.2): Magnets with Particles

Description: Magnet creates magnetic pulse which directs particles in desired direction

Primary Actors: Particles

Primary Objects: Magnets

Pre-conditions: The particles have to be coupled with ferro-magnetic particle in order to react as predicted in response to the magnetic pulse. Also, particles do not interact with surrounding channel other than in response to changes in the magnetic field. Channel geometries are known and cannot interfere with particle steering.

Flow of events:

1. Desired path is entered by researcher
2. Particles coupled with ferro-magnetic particle are introduced to system
3. Sensor senses particles position
4. Computer analyzes path based on inputted path
5. Control algorithm activates magnets based on computer analysis
6. Magnets activate, creating flow and steering particle
7. Sensor senses position and the process loops

Post-conditions: Reaction of particles coupled with ferro-magnetic particles known, can be steered reliably along a path

Scenario (1.2.1): Magnets Steer Cells Coupled with Ferro-Magnetic Particles

Description: Magnets create magnetic pulses that act on cells, which are linked to ferro-magnetic particles. The pulse will direct the cells in the desired direction.

Primary Objects: Magnets and cells coupled with ferro-magnetic particles.

Pre-conditions: All cells are linked or tagged with ferro-magnetic particles to allow for predicted interaction with magnetic pulse. Also, cells do not interact with surrounding channel other than in response to changes in the magnetic field. Channel geometries are known and cannot interfere with particle steering.

Flow of events:

1. Desired path is entered by researcher
2. Cells coupled with ferro-magnetic particle are introduced to system
3. Sensor senses cell's position
4. Computer analyzes path based on inputted path
5. Control algorithm activates magnets based on computer analysis
6. Magnets activate, creating flow and steering particle
7. Sensor senses position and the process loops

Post-conditions: Path of the cells is known and can particles can be reliably steered.

Scenario (1.2.2): Magnets Steer Ions Coupled with Ferro-Magnetic Particles

Description: Magnets create magnetic pulses that act on ions, which are linked to ferro-magnetic particles. The pulse will direct the ions in the desired direction.

Primary Objects: Magnets and ions coupled with ferro-magnetic particles.

Pre-conditions: All ions are linked or tagged with ferro-magnetic particles to allow for predicted interaction with magnetic pulse. Also, ions do not interact with surrounding channel other than in response to changes in the magnetic field. Channel geometries are known and cannot interfere with particle steering.

Flow of events:

1. Desired path is entered by researcher
2. Ions coupled with ferro-magnetic particle are introduced to system
3. Sensor senses ion's position
4. Computer analyzes path based on inputted path
5. Control algorithm activates magnets based on computer analysis
6. Magnets activate, creating flow and steering particle
7. Sensor senses position and the process loops

Post-conditions: Path of the cells is known and can particles can be reliably steered.

Sequence Diagram for Use Case 1

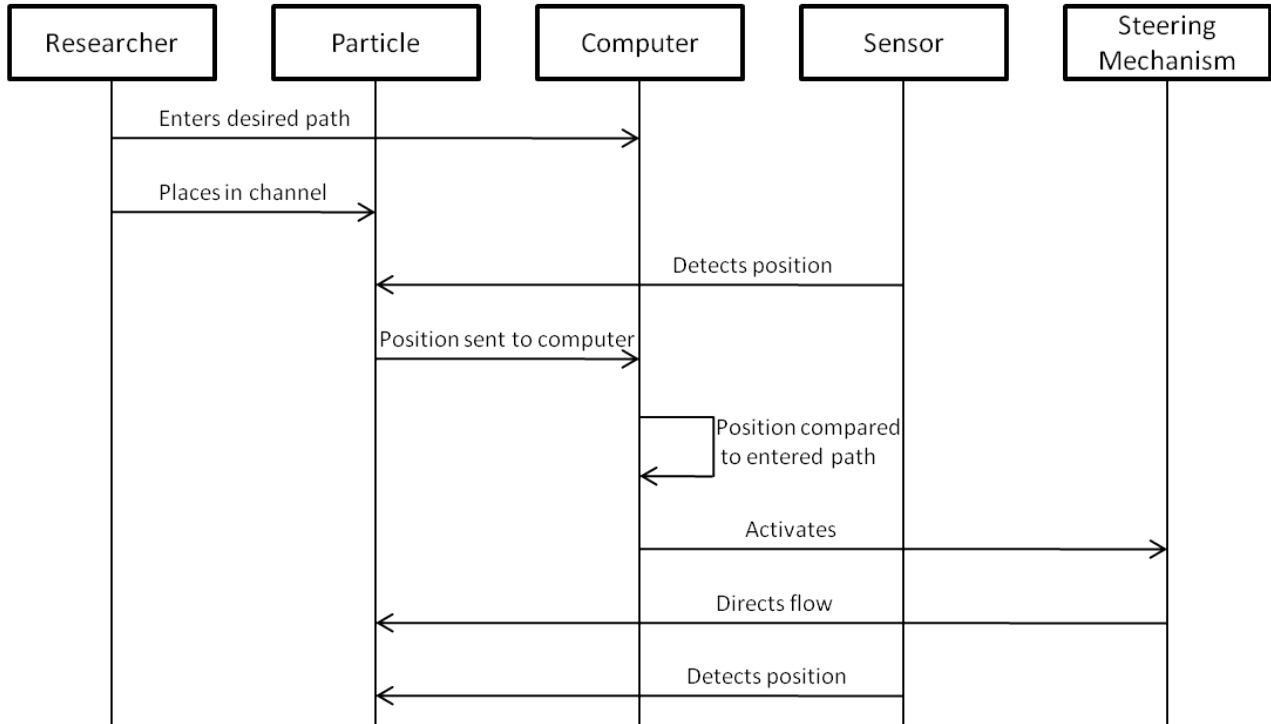


Figure 7 – Sequence diagram for the first use case.

Use Case 2: Maximizing Accuracy

The second use case explores the maximum accuracy available depending on the optical sensors, control algorithm, which includes the allowed margin of error and measurement interval. Each one of these can be optimized to result in the more effective movement of the particle along the desired path. A variety of optical sensors filters can be selected in order to track particles of a given wavelength. Each may have its own advantages and disadvantages when measuring the particle positions. Likewise, the control algorithm can be modified to react with a set or proportional magnitude to the error detected, therefore also effecting the accuracy of the particle movement. Lastly, the sample interval set by the researcher will determine how fast and often (samples per second) the optical sensor tracks the particle. The more often a sample is taken, the more frequent the actuators will move the fluid appropriately.

Scenario (2.1): Optical Sensor Filters

Description: Optical sensor filters detect specific wavelengths emitted by fluorescently labeled particles while rejecting noise.

Primary Actor: Researcher

Primary Objects: Optical sensor

Pre-conditions: Optical sensor filters are set to detect wavelengths specific to the ones emitted by the used particle

Flow of events:

1. Researchers chooses specific wavelength
2. Researcher activates sensor
3. Sensor searches for particle
4. Sensor determines if particle is the desired particle versus an unrelated particle by detecting its wavelength
5. Sensor sends information to computer for processing

Post-conditions: Sensor is able to detect and collect needed information from particle.

Scenario (2.1.1): Fluorescent Label

Description: Particles can be tagged with a variety of different fluorescent labels, which emit different wavelengths of light.

Primary Actor: Researcher

Primary Objects: Optical sensor and fluorescent particle

Pre-conditions: Optical sensor filters are set to detect wavelengths specific to the ones emitted by the used particle. There has to be a long-term attachment between the particle and the fluorescent tag

Flow of events:

1. The researcher tags the particles with a fluorescent label
2. The researcher places the particles in the channel and begins experiment
3. The optical sensor detects the specific fluorescent wavelength and determines location of particle

Post-conditions: Sensor is able to detect and collect needed information from particle based on a specific fluorescent wavelength

Scenario (2.2): Control Algorithm

Description: The control algorithm processes information detected by the sensors and determine appropriate actuator response

Primary Actor: Researcher

Primary Objects: Computer

Pre-conditions: Control algorithm follows steps set by researcher

Flow of events:

1. Researchers designs control algorithm
2. Computer receives information from sensor
3. Computer implements control algorithm to determine error
4. Control algorithm determines necessary response for actuators to eliminate error

Post-conditions: Control algorithm is able to send appropriate response for error correction

Scenario (2.2.1): Margin of Error

Description: Based on the error allowed, the control algorithm makes necessary adjustments

Primary Actor: Researcher

Primary Objects: Computer

Pre-conditions: Control algorithm follows steps set by researcher

Flow of events:

1. Researcher designs control algorithm and sets sensitivity (margin of error)
2. Computer receives information from sensor
3. Computer implements control algorithm to determine error
4. Control algorithm determines appropriate magnitude of response for actuators to eliminate error

Post-conditions: Control algorithm is able to send appropriate magnitude of response for error correction

Scenario (2.2.2): Measurement Interval

Description: The measurement interval determines how often a sample is taken within a set amount of time

Primary Actors: Researcher

Primary Objects: Optical Sensor, computer, and control algorithm

Pre-conditions: Control algorithm follows steps set by researcher within desired measurement interval

Flow of events:

1. Researchers designs control algorithm and sets measurement interval
2. Computer receives information from sensor
3. Computer implements control algorithm to determine error
4. Control algorithm determines appropriate response for actuator
5. Repeats steps 2-4 at sample rate set by researcher

Post-conditions: Control algorithm is able to send appropriate response at certain sample rate

Use Case 3: Maximizing Performance

The third use case considers the possibility of maximizing the performance (i.e. speed) of the particle steering device. Depending on the system, the rapidity with which particles can be returned to the entered path may have greater or less significance to the researcher. The performance of the device can be altered by the fluid type used in the channel, the channel

dimensions, and the arrangement of actuators within the channel. Scenarios for these aspects are explained in greater detail below:

Scenario (3.1): Fluid Type

Description: The particles are contained in the system within a fluid. The fluid flows based on the output of the steering mechanism, which carries the particles to their proper position.

Primary Actor: Researcher and particles

Pre-conditions: The fluid reacts as expected to the corresponding steering mechanism.

Flow of events:

1. The researcher selects appropriate fluid based on desired steering mechanism and particle type.
2. The fluid is moved by actuator signals therefore transporting particles in the same direction.
3. Fluid flow continues until sensors indicate particles are in proper position and actuators turn off.

Scenario (3.2): Channel Dimensions

Description: The fluid and particles are contained by channels with given dimensions. These dimensions determine fluid flow and particle interaction.

Primary Actors: Researcher and particles

Primary Objects: Channel and Fluid

Pre-conditions: Channel dimensions must be at the micro-level in order to simplify momentum effects within the system and allow actuators to reliably steer particles. Dimensions must allow for laminar flow.

Flow of events:

1. The researcher selects appropriate channel dimensions based on desired fluid flow and steering mechanism..
2. Channels redirect flow depending on actuator signals.

Scenario (3.3): Arrangement of Steering Mechanism

Description: The arrangement of the steering mechanism within the channel determines the direction and/or response of the fluid, and therefore the particles. In addition, the location and geometry of the actuators relative to each other will affect the flow of the fluid.

Primary Actor: Researcher

Primary Objects: Steering mechanism

Pre-conditions: Arrangement of steering mechanism has to allow for full control of the fluid within the main area of the channel.

Flow of events:

1. The researcher selects appropriate arrangement of the steering mechanism based on channel shape and desired fluid flow.
2. Selective actuators activate depending on the arrangement and desired particle movement.

REQUIREMENTS AND TRACEABILITY

1. Steering Mechanism Requirements

1. Arrangement of the steering mechanism must allow for movement of particle in any direction
2. Particles must be coupled to ferro-magnetic particles when actuators are magnets
3. The steering mechanism must be supplied enough power to create fluid flow
4. The steering mechanism must react within a certain amount of time after it receives data from the control algorithm
5. The steering mechanism has to be cost effective

2. Particle Requirements

1. Particles have to be small enough to flow within channel
2. Particles must be tagged with a fluorescent label

3. Fluid Flow Requirements

1. The fluid flow must be laminar within the channel
2. Fluid does not interfere with optical sensor and its function
3. When cells are used as particles, the fluid must be a cell culture media in order to sustain cell viability.

4. Control Algorithm Requirements

1. The control algorithm has to work at a certain processing speed
2. It must use a set margin of error to calculate the response of the actuator

5. Computer Requirements

1. Must accurately transmit information between the optical sensor, control algorithm, and steering mechanism
2. The computer must be able to transfer data within the components as fast, if not faster, than the control algorithm processes it

6. Sensor Requirements

1. Optical sensor must filter out the proper wavelengths in order to accurately trace particles
2. Optical sensors must have a wide field of view to see particles at any location within the channel

7. Channel Requirements

1. Channel must be micron sized to reduce momentum effects
2. Channel must not react with particles or fluid

Traceability Matrix from Requirements to Use Cases

Use Case	Scenario	Req. No.	Description
Particle Steering	Scenario 1.1 & 1.2	Req. 1.3	Steering mechanism must have enough power to create fluid flow
	Scenario 1.2	Req. 1.2	Particles must be coupled to ferro-magnetic particles if actuators are magnets
	Scenario 1	Req. 2.1	Particles have to be small enough to flow within channel
	Scenario 1.1.1 & 1.2.1	Req. 3.3	Cell culture media must be used if cells are the particles
Maximizing Accuracy	Scenario 2.1	Req. 3.2	Fluid does not interfere with the optical sensor's function
		Req. 6.1	Optical sensor must filter out the proper wavelengths in order to trace particles
		Req. 6.2	Optical sensor must have a field of view that allows it to see particles at any location within the channel
	Scenario 2.1.1	Req. 2.2	Particles must be fluorescently labeled
	Scenario 2.2.2	Req. 4.1	Control algorithm must work at a certain processing speed
		Req. 5.2	Computer must be able to transfer data at least as fast as the control algorithm processes it
	Scenario 2.2.1	Req. 4.2	Control algorithm must use set margin of error to calculate response of the actuator
Scenario 2	Req. 5.1	Computer must accurately transmit information between the optical sensor, control algorithm, and steering mechanism	
Maximizing Performance	Scenario 3.3	Req. 1.1	Steering mechanism must allow for movement of particle in any direction
	Scenario 3	Req. 1.4	Steering mechanism must react within a certain amount of time after it receives data
	Scenario 3.2	Req. 3.1	Flow must be laminar within the channel
		Req. 7.1	Channel must be micron-sized to reduce momentum effects
	Scenario 3.1 & 3.2	Req. 7.2	Channel must not interact with particles or fluid

Table 1 – Relation of higher level requirements to scenarios and use cases.

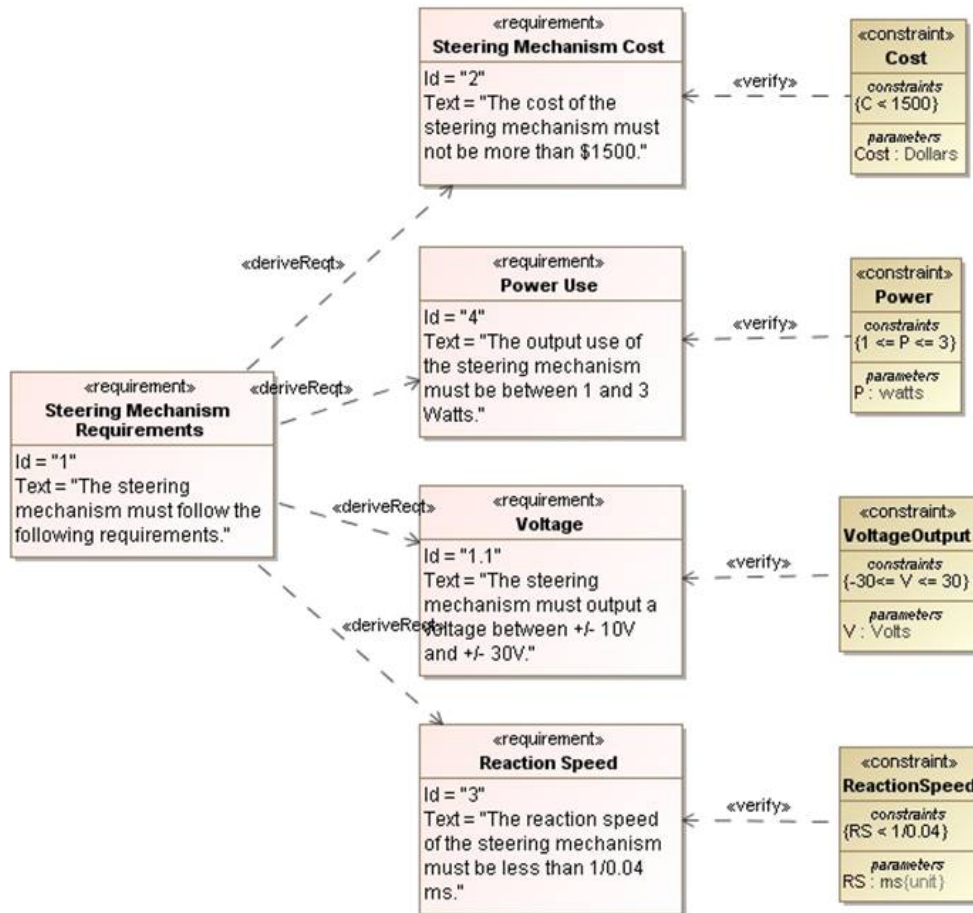
Specifications

#	Requirements	Specification
1	Electrode steering mechanism must put out a certain voltage.	+/- 10V - +/- 30V
2	The steering mechanism must have requisite power to create electric flow	~min of 1 watts, max of 3 watts (with 30V and 100mA inputs)
3	Steering mechanism must react within an appropriate time scale	< 1/40 second
4	Steering mechanism must be cost effective	< \$1500
5	When cells are used, the population must stay above a certain concentration of viable cells	10 ³ cells/mL
6	There cannot be more than the maximum number of particles capable of being steered	Maximum of 3 particles for an 8 electrode system
7	Particles must be small enough to flow through channel	< 30 microns
8	The fluorescent label has to emit light which is visible to a fluorescent sensor	510nm for green, 650 for red, 350 for blue
9	The fluid must exhibit laminar flow	Reynold's number < 2000
10	Fluid must have reasonable permittivity and viscosity	Permittivity ~ 80.1 F/m Viscosity ~ 0.001 Pa*s (water)
11	The fluid has to be optically clear and transparent	index of refraction <= ~ 1.33
12	Processing speed of computer must be as fast, or faster than that of the control algorithm	< 1/40 sec per process
13	The size of the channel must not induce momentum effects	Size < 100 microns in depth and width
14	The device must be cost effective	~ \$5000

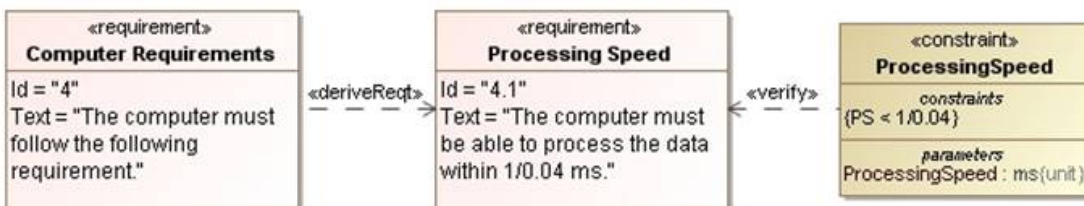
Table 2 – Table of requirements and their derived constraints.

Requirement Diagrams

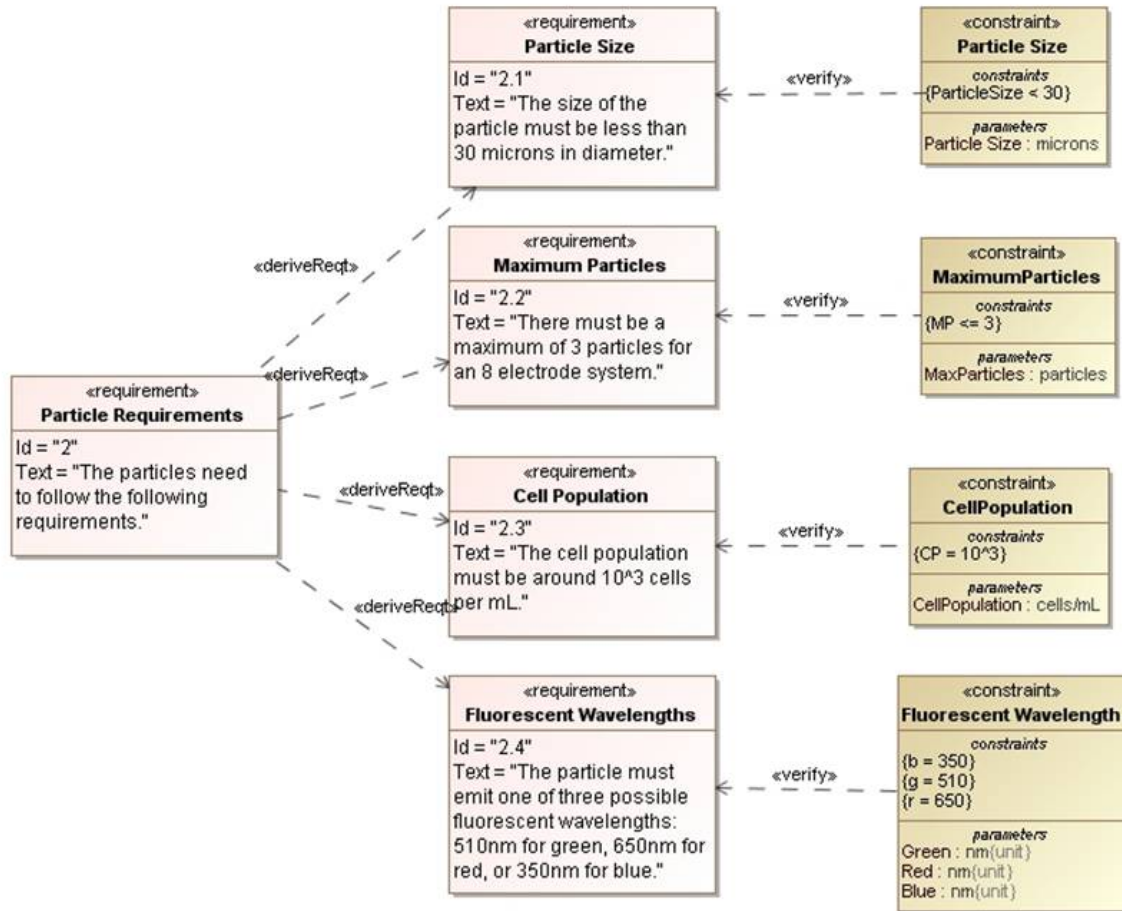
Steering Mechanism Requirements Diagram



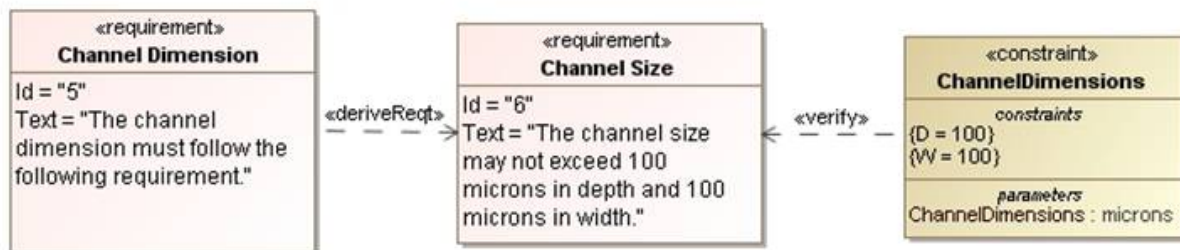
Computer Requirements



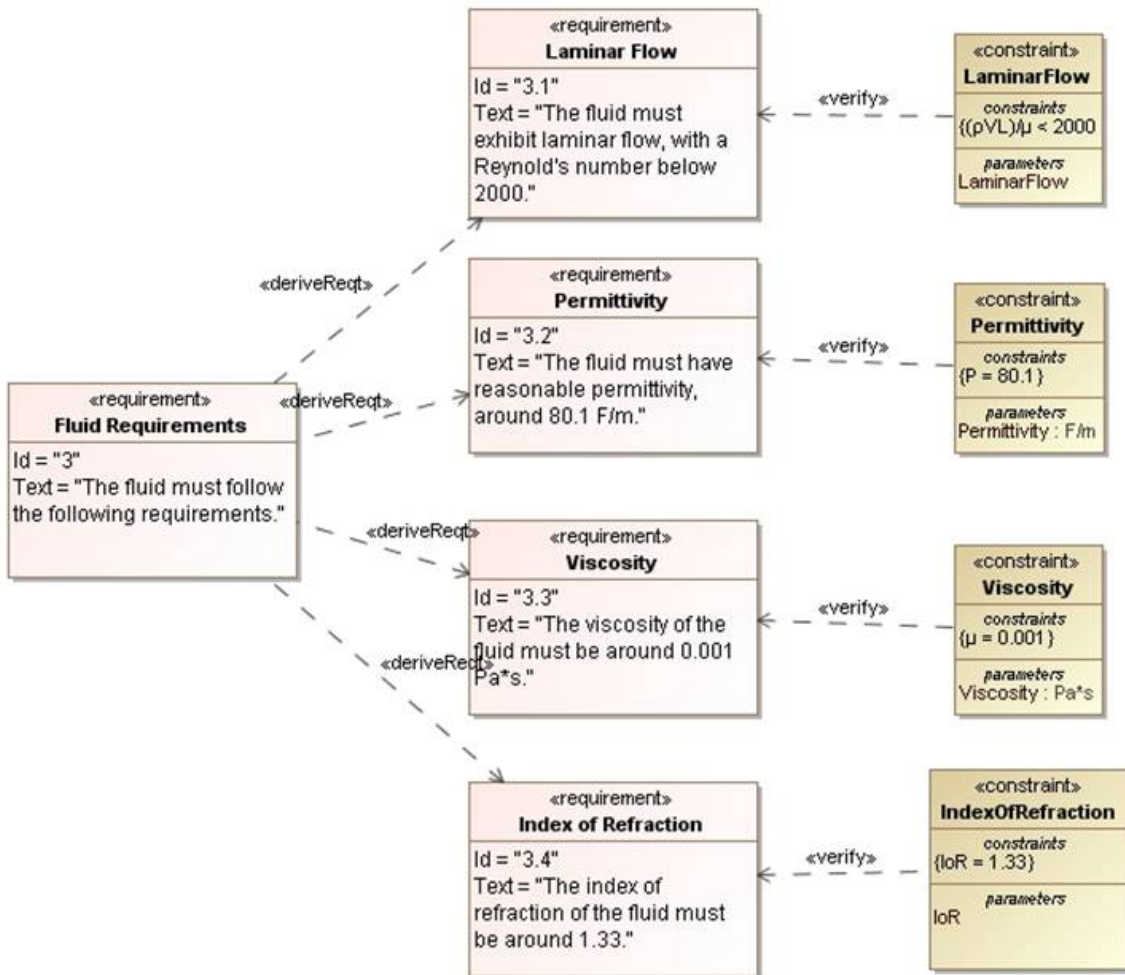
Particle Requirements Diagram



Channel Requirements



Fluid Requirements



Traceability of Design Options to System Level Requirements

<u>Components</u>	<u>Performance</u>	<u>Accuracy</u>	<u>Cost</u>
Steering Mechanism			
Power	+	-	+
Reaction Time	-	-	-
Particle Type			
size	o	+	+
Fluid			
viscosity	-	+	o
Optical Sensor			
Power	o	+	+
Frequency	o	+	+

Table 3 - Component effect on system level requirements based on an increase in the parameter

<u>Legend:</u>				
Performance:	+	faster time,	-	slower time
Accuracy:	+	less error,	-	more error
Cost:	+	more expensive,	-	less expensive
o = no effect				

Traceability of Components to System Requirements

The system requirements are performance, accuracy, and cost. Performance is measured by the amount of time it takes for the particle to follow the entire path, measured in milliseconds. The accuracy describes the deviation of the actual path from the desired path. Lastly, the cost is the sum of the cost of the components.

Steering Mechanism

- **Power:** The power describes the Watts consumed by the steering mechanism, depending on the voltage supplied to it.
 - **Performance:** Performance is increased when the power consumed by the steering mechanism is increased. This means that the more Watts are consumed, the faster the particle is able to trace the entire path.
 - **Accuracy:** Accuracy is decreased when power consumption is increased. The more power is used, the further the particle deviates from the desired path.
 - **Cost:** The cost increases as more power is used. It is more expensive to purchase a steering mechanism that requires more power.

- Reaction Time: The reaction time quantifies the amount of time it takes for the steering mechanism to respond to data processed by the control algorithm.
 - Performance: The performance decreases when the reaction time of the steering mechanisms increases. The longer it takes the steering mechanisms to react, the longer it takes the fluid flow to occur, which in turn means it will take the particle longer to complete the path.
 - Accuracy: The accuracy of the system decreases with the increase in reaction time. When the reaction time is longer, error is fixed more slowly, allowing for greater deviation off the path.
 - Cost: The cost decreases as the reaction time increases because it delivers lower performance and accuracy to the system.

Particle Type

- Size: Possible particles come in a variety of sizes (measured in microns).
 - Performance: The size has a negligible effect on the performance, when compared to the other parameters. Therefore, we assume that a reasonable increase in particle size will have no significant effect on the performance of the system.
 - Accuracy: Accuracy increases when the size of the particle increases because the deviation from the desired path is small in comparison to the size of the particle.
 - Cost: The cost of the system becomes more expensive as the size of the particle increases. This is due to the fact that larger particles tend to be more complex, which in turn makes them more expensive.

Fluid

- Viscosity: The viscosity of the fluid describes the resistance of the fluid to deformations. It is measured in Pascal seconds (Pa*s).
 - Performance: The performance of the system is decreased when the viscosity of the fluid is increased. This is due to the increased resistance of the fluid, which increasing the time it takes for the particle to traverse the path.
 - Accuracy: The accuracy of the system is increased as the viscosity of the fluid is increased because the particle travels slower through a more resistant fluid. Therefore, the particle's path deviates less from the wanted path.
 - Cost: The cost of the system is not affected by the increase in viscosity. A more viscous fluid is not more expensive than a less viscous fluid.

Optical Sensor

- Power: The power describes the Watts consumed by the optical sensors, depending on the voltage supplied to it.

- Performance: The power consumed by the optical sensor does not affect the performance of the system because the sensor is not directly related to the speed of the particles.
- Accuracy: The accuracy increases with the increase in power to the optical sensors. More power allows the optical sensor to identify larger ranges of fluorescent wavelength, therefore increasing the chance of detecting a particle. Therefore, the particle will deviate less from the desired path.
- Cost: The cost increases as more power is used. It is more expensive to purchase an optical sensor that requires more power because it delivers greater accuracy.
- Frequency: The frequency describes the rate at which the optical sensor determines the location of the particles. It is measured in frames per second.
 - Performance: The performance of the system remains unchanged when the frequency of the optical sensor is increased because the sensor has no direct effect on the speed at which the particle moves along the path.
 - Accuracy: The accuracy of the system is increased as the frequency of the optical sensor increases. This means that the optical sensors are able to detect a deviation of the particle from the path as soon as it deviates. Therefore, smaller deviations occur before they are corrected.
 - Cost: The cost of the system increases when the frequency of sampling of the optical sensor increases. An optical sensor with a higher sampling frequency costs more to construct, therefore making it a more expensive component.

TRADE-OFF ANALYSIS

The trade-off analysis focuses on three system level-aspects as mentioned above: Cost, accuracy, and performance. For each component mentioned above, three different design options were considered. For each design in the trade-off analysis, a system is considered that possesses one option from each of the six design variables possible. For each option, its effect on the performance, cost, and accuracy were assessed and then quantitatively determined based on the requirements and specifications derived earlier as well as information from previous papers. The table below displays the quantitative value of each component on the three system-level requirements.

<u>Steering Mechanism</u>				
Power				
Options	Power (watt)	Performance (s)	Accuracy (μm)	Cost (\$)
1	1	90	0.7	1000
2	2	80	0.8	1500
3	3	70	0.9	2000
Reaction Time				
Options	Time (ms)	Performance (s)	Accuracy (μm)	Cost (\$)
1	5	75	0.7	500
2	15	80	0.8	400
3	25	85	0.9	300
<u>Particle Type</u>				
Size				
Options	size (microns)	Performance (s)	Accuracy (μm)	Cost (\$)
1	0.01	n/a	0.9	300
2	0.1	n/a	0.8	400
3	10	n/a	0.7	500
<u>Fluid</u>				
Viscosity				
Options	Viscosity (Pa*s)	Performance (s)	Accuracy (μm)	Cost (\$)
1	0.0005	70	0.7	0
2	0.001	80	0.8	0
3	0.005	90	0.9	0
<u>Optical Sensor</u>				
Power				
Options	Power (watt)	Performance (s)	Accuracy (μm)	Cost (\$)
1	1	n/a	0.7	500
2	2	n/a	0.8	400
3	3	n/a	0.9	300
Frequency				
Options	Frequency (Frames/s)	Performance (s)	Accuracy (μm)	Cost (\$)
1	50	n/a	0.7	1000
2	40	n/a	0.8	750
3	30	n/a	0.9	500

Table 4 – Design Options and their respective effects on the system-level requirements.

Based on the values that were obtained from table 4, system designs were considered by choosing certain combinations of the design variables. One example of a system is given below:

System 12

SM Power	Options	Power (watt)	Performance (s)	Accuracy (µm)	Cost (\$)
	2	2	80	0.8	1500
Reaction Speed	Options	Time (s)	Performance (s)	Accuracy	Cost (\$)
	3	25	85	0.9	300
Particle Type	Options	size (microns)	Performance (s)	Accuracy	Cost (\$)
	1	0.01	n/a	0.9	300
Fluid	Options	Viscosity (Pa*s)	Performance (s)	Accuracy	Cost (\$)
	1	0.0005	70	0.7	0
OS Power	Options	Power (watt)	Performance (s)	Accuracy	Cost (\$)
	3	3	n/a	0.9	300
Frequency	Options	Frequency (Frames/s)	Performance (s)	Accuracy	Cost (\$)
	1	50	n/a	0.7	1000

Table 5 – One possible system arrangement of the component design variables.

Possible combinations of system arrangements were determined based on this method to provide a basis for trade-off analysis and creating plots for Pareto analysis. There are 256 possible combinations of design components, but for the purposes of this report only 15 are considered. In order to carry out Pareto analysis each systems-level requirement for a potential combination is normalized by the following equations:

$$P_{SM} = 0.6P_{SM} + 0.1P_{RS} + 0.3P_{PT} \quad (1)$$

$$P_{OS} = 0.1P_{OS} + 0.2P_{OS} + 0.05P_{OS} + 0.05P_{OS} + 0.4P_{OS} \quad (2)$$

$$C_{total} = C_{SM} + C_{RS} + C_{PT} + C_{OS} + C_{F} \quad (3)$$

The equations given above were determined based on the estimated weight each design variable would have on a given requirement. For example, the power of the steering mechanism has the most significant effect on the performance of a system so it was weighted 60% of the total performance whereas the reaction time was weighted 10% and the viscosity 30% of the total performance. The accuracy equation was developed in a similar fashion and the cost equation was assumed to be a simple addition of the cost of each component.

After normalization the different system arrangements they were plotted on three different plots: cost vs. performance, cost vs. accuracy, and performance vs. accuracy as shown below.

System Combinations	Performance	Accuracy	Cost
System 1	82.5	0.71	3300
System 2	80	0.8	3450
System 3	77.5	0.89	3600
System 4	83	0.73	3200
System 5	82.5	0.705	3400
System 6	85.5	0.73	3300
System 7	82.5	0.715	3200
System 8	82.5	0.75	3050
System 9	82.5	0.765	3700
System 10	73.5	0.83	4500
System 11	86.5	0.77	2400
System 12	77.5	0.77	3400
System 13	89.5	0.88	2400
System 14	79.5	0.735	3900
System 15	89.5	0.835	2750

Table 6 – List of System combinations and calculated system-level requirement values.

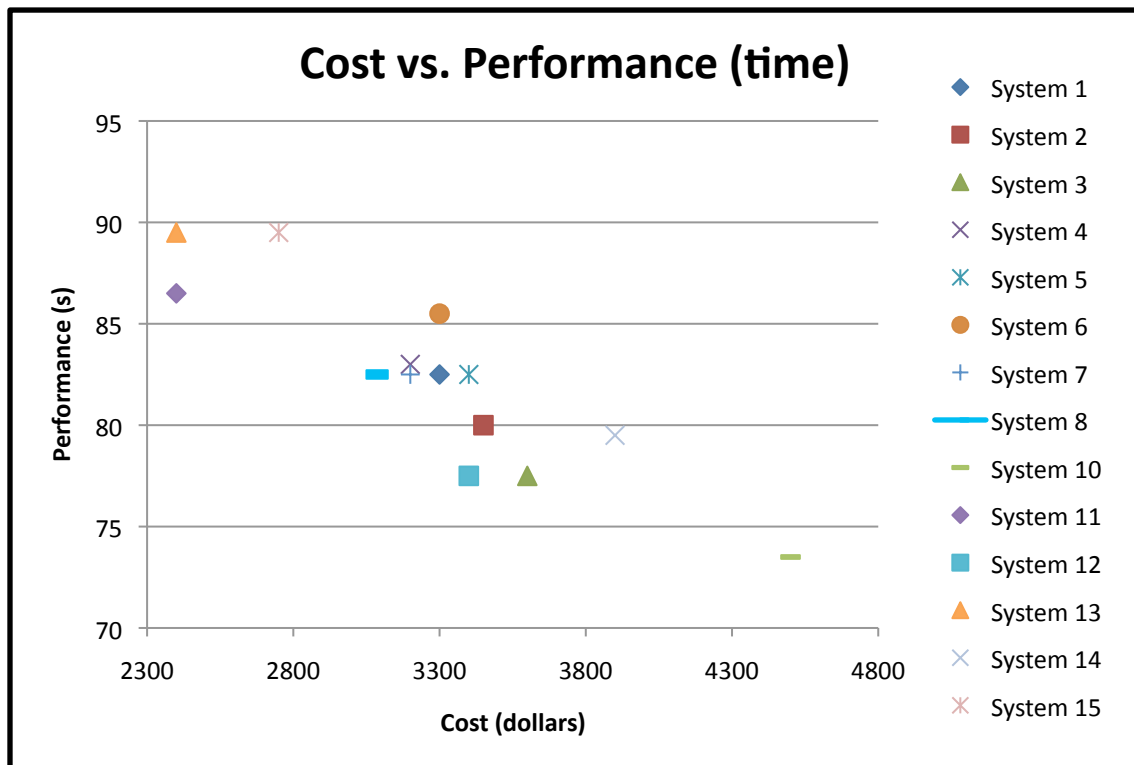


Figure 8 – Graph of the cost versus performance trade-off analysis

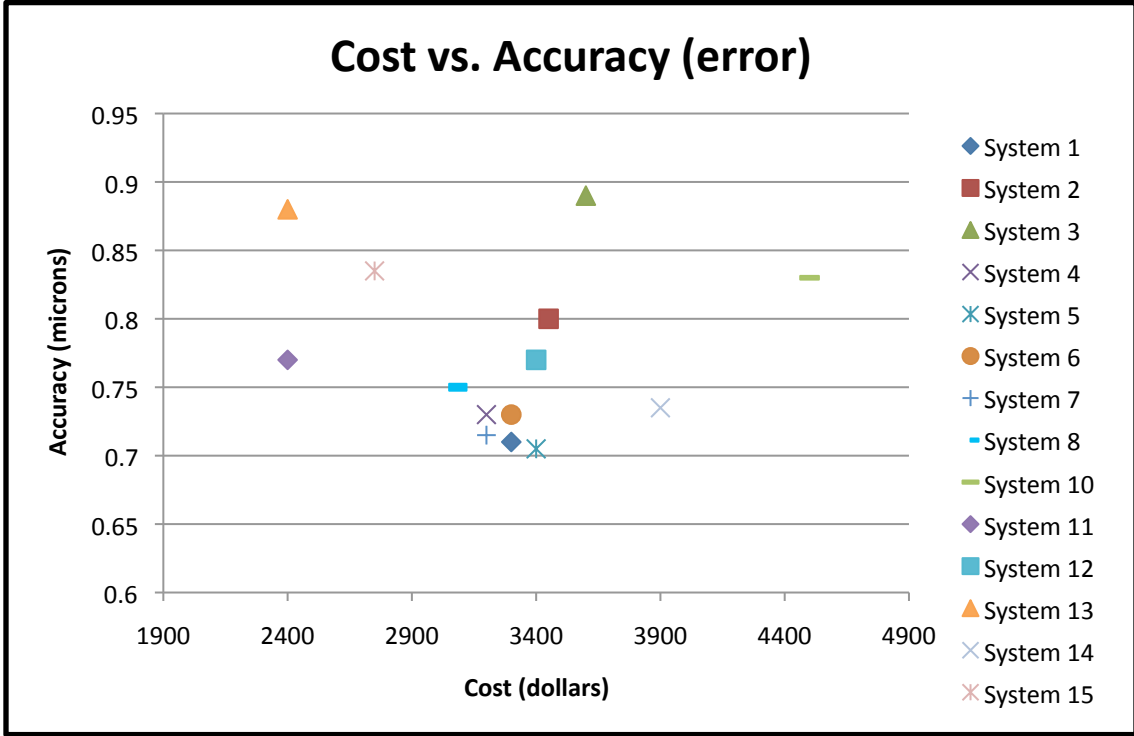


Figure 9 – Graph of the cost versus accuracy trade-off analysis

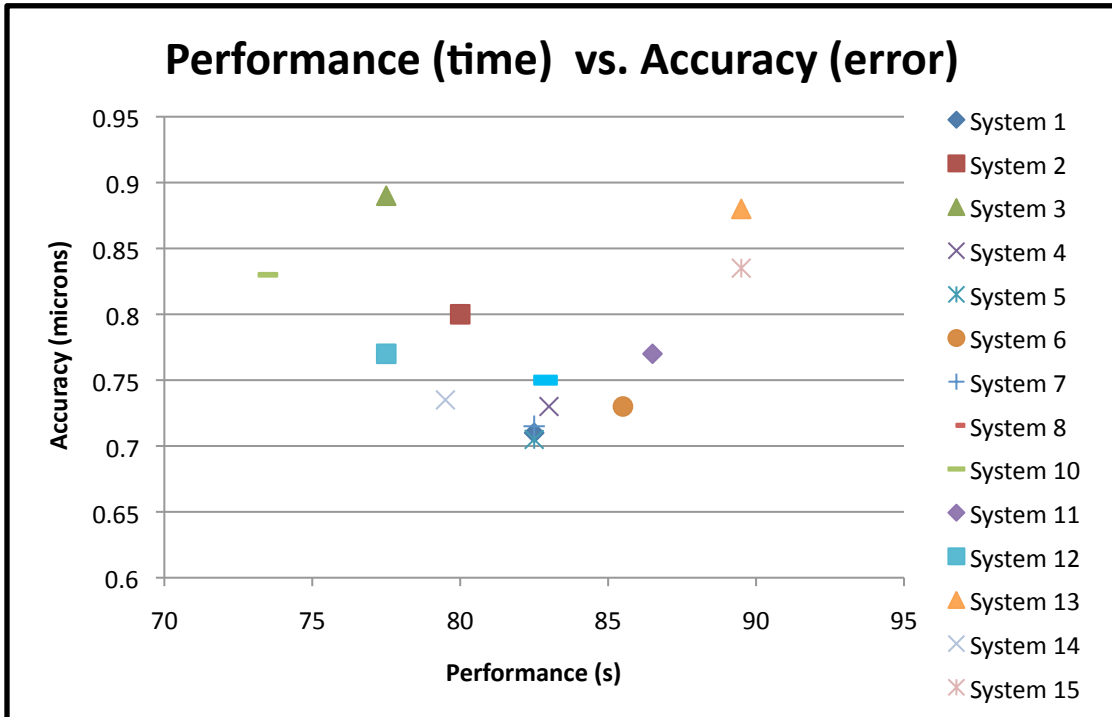


Figure 10 – Graph of performance versus accuracy trade-off analysis

Pareto Analysis

The graphs above show several points of interest that can be considered more thoroughly using Pareto analysis in order to determine the optimal combination. It is important to note that the performance is measured in the time it takes for the particle to follow a path and accuracy is measured by the deviation of the path. With this in mind, the optimal placements of the points are toward the origin.

Starting with the cost versus performance graph, a clear trend can be seen. As performance increases, so does the cost of the entire system. Although there are a number of points that are relatively cheap, they deliver poor performance. Similarly, System 10 brings high performance at the expense of greatly increased cost. Therefore, these outliers are not considered for the system. Systems 2, 3, and 12 are in a similar area on the chart and can be easily compared. By comparison, System 2 has slightly worse performance, as well as costs more than System 12. Therefore System 12 would be a more advantageous choice. Next, System 3 delivers the same performance as System 12 yet costs more. Based these observations, it can be determined that System 12 holds dominance over Systems 2 and 3 in terms of cost and performance. Systems 8 and 12 can also be compared. System 8 has lower performance but also costs less. The decrease in cost is of a similar magnitude as the decrease in performance, therefore should be considered.

Next, the cost versus accuracy can be analyzed. No clear trend can be observed between cost and accuracy because performance has a great effect on cost than accuracy. In addition, performance tends to decrease the accuracy of the system, making it difficult to characterize cost versus accuracy. Points of interest for this graph are Systems 1, 7, and 11. Systems 1 and 7 are close in cost and accuracy and have higher accuracy per cost compared to systems around them. System 11 has a lower accuracy than 1 and 7 but is substantially cheaper. Given this dramatic decrease in cost compared to loss in accuracy, System 11 is the optimal point in this graph.

Lastly, performance versus accuracy can be compared. Two dominant points in this graph are Systems 1, 12, and 14. System 12 has worse accuracy but better performance than Systems 14. Likewise, System 14 has worse accuracy and better performance than System 1. The trade-off between performance and accuracy for these points is proportional. Therefore, all three could be considered depending on which requirement the user seeks to maximize.

In order to find the best combination of design variables, a simultaneous consideration of all three graphs is necessary. Systems 1, 8, 11, 12, and 14 were combinations considered for the individual trade-offs. However, they must now be considered as a whole. When analyzing these systems in the cost versus performance graph, it is clear that System 11, although relatively cheap, offers very poor performance compared to the other systems. Therefore, this rules out System 11. Systems 1 and 8 have similar performance, but System 1 costs more than System 8, indicating that it might not be a good choice for the given system. System 14 has considerable cost, as well as low performance compared to Systems 1, 8, and 12, but the discrepancies are not large enough to rule it out just yet.

Next, consideration of each point in the cost versus accuracy graph needs to be made. System 11 was the optimal point, and while system 12 costs significantly more it delivers the same accuracy as system 11. However as noted above, System 11 delivers much less performance and is therefore ruled out since it only has advantages in cost over other options. Comparing Systems 12 and 14 on this chart shows that System 14 has slightly better accuracy

than System 12 but costs much more. Given the above analysis, System 12 has better performance, similar accuracy, and much lower cost than System 14, so System 14 can also be ruled out as the optimal combination. System 1 has better accuracy than System 8, but also costs more. Given that System 1 costs more than System 8 but provides worse performance and only marginally better accuracy, System 1 can be ruled out as a possible option. System 8 provides higher accuracy and lower cost than System 12 but not a significant amount. Therefore neither system can be ruled out yet.

An examination of the performance versus accuracy graph helps to distinguish the best point between Systems 8 and 12. While System 8 has slightly higher accuracy than System 12, System 12 has significantly higher performance than System 8. Considering that System 12 offers similar accuracy and much greater performance, at only slightly higher cost than System 8, it can be determined that system 12 is the optimal point in this analysis.

VALIDATION AND VERIFICATION

Validation is the method by which the system is tested on where or not it adheres to the technical requirements set forth by the customer. Verification, on the other hand, is a method to test if the system is able to function as intended by the design requirements. Although the actual validation and verification process is beyond the scope of this course, below are possible ways describing how these methods can be completed.

Validation

There is an overall requirement set by the customer, dictating that the device be able to steer a particle a long a specific path entered by the research. In order to validate the device, one of two possible methods can be done:

- Building one or more variations of the device using the specifications provided by trade-off analysis
- Using a computational fluid dynamics software to model the system theoretically before building it

Verification

The verification of the systems is dependent on its ability to fulfill specific requirements. These include being able to steer the particle along a pathway within a specific time frame with minimal deviation. To verify that the device fully satisfies the design requirements, the following methods can be utilized:

- Building one or more variations of the device using the specifications provided by trade-off analysis
 - Test the steering mechanism for its ability to steer a particle in any direction and then along a determined path
 - Time the particle's performance as it is steered along the path
 - Measure the maximum deviation from the path of the particle under certain conditions

- Using a computational fluid dynamics software to model and verify the system theoretically before building it for each of the above parameters

Once the system has been verified and validated to fit the system-level requirements, the device can be manufactured within the given specifications and delivered to the customer.

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