Preliminary Design Report

Project – Zen and the Art of Glitter Deposition

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Problem Statement

Our client is Integrity Industrial Inkjet Integration, a company that applies inkjet technology to design innovative production lines across various industries. The client would like the group to develop proof of concept for a module that will coat a layer of adhesive with glitter and reuse any glitter that does not stick. The module would be used in tandem with their current inkjet and UV curing light setup to stack layers of powder and adhesive. The module would improve production efficiency and save material across several industries. The current method utilizes a curtain of powder, which results in large amounts of waste material. By only using a small amount of powder and mixing it around a small container, the module would effectively utilize all the material for coating instead of creating a powder curtain.

The main functions required for this device are to control the amount of glitter deposited, ensure the adhesive is completely coated, and remove any excess glitter. Solving this problem will impact many manufacturing industries for it will be a new way to 3D print certain products, with a buildup of powder running through multiple times. It will also enable Integrity to build upon the concept and create a new line of manufacturing for them.

Customers' Requirements

The group identified three potential customers and produced a table of prioritized requirements based on the needs of each of the clients. The three customers were: Integrity, the customers of Integrity, and conveyor technicians. Each requirement was given a score to represent its importance to each customer and each customer was given a different number of points to represent the weight of their opinion.

Table 1: Customer Requirements

Customers				Requirements	
Integrity	Integrity's Customers	Conveyor Technicians		Category	Requirement
5	3	-		*Functionality*	Must be able to easily run multiple colors of glitter when running in series
13	**10**	**-**			**Remove excess glitter without removing adhered particles**
15	**10**	**-**			**Glitter covers the adhesive efficiently**
9	5	**10**			**Ensure minimal glitter escapes the box**
6	-	5			Box must be securely mountable to Integrity's conveyor system
10	-	-			Must not take up too much space on Integrity's conveyor
5	5	10			Operates for long durations reliably

13	**7**				**Glitter must be randomly and evenly distributed across adhesive**
8	5	**10**		*Safety*	**Box must have zero risk for particle ignition**
8	5	**10**			**A way to easily control device to stop or divert the glitter flow**
8	-	5		*Aesthetic*	Box shall have a way to clearly observe particle flow within it

The three highest scored requirements for each client have been bolded in the above table. For Integrity and their clients, the top three requirements match as their priorities are similar. For the conveyor technician, the highest-level requirements focus on potential hazards when operating the module.

The highest-level requirement for both Integrity and their clients was, “Glitter covers the adhesive efficiently”, this is a fundamental function of the module. One of the main purposes of the module is to reduce material waste, if this cannot be accomplished then the module has failed. Both Integrity and their clients want to have the best coating while using the least amount of material. The second high-level requirement for Integrity and their clients was, “Remove excess glitter without removing adhered particles”. This is an important requirement because if glitter that has been adhered gets removed work has effectively been undone and that material cannot be used again. This requirement shares the same source of relevance as the first, Integrity and their clients need the box to perform its core functions and if adhered glitter is removed then the box has failed. The third high-level requirement is that “Glitter must be randomly and evenly distributed across adhesive”. An important function of the module is that a part should have a full coat of glitter after one pass through the module. If there are patches where no glitter lands, the process of stacking multiple layers would result in an uneven and rough three-dimensional surface.

The high-level priorities for the conveyor technicians focus on making the module easy and safe to operate. The first high-level requirement is “Box must have zero risk for particle ignition”. The module is intended to be used with a wide range of powders, including some powders that are flammable. Ensuring the safety of the technician and other individuals near the module is a necessity. Because of this, any risk of ignition must be mitigated. The next high-level requirement is, “Ensure minimal glitter escapes the box”. As a conveyor technician, making sure the line runs smoothly is very important. Powder being blown out of the box could be a hazard for any individuals in the vicinity of the box, additionally expelled powder could interfere with other components on the production line. The third high-level requirement is, “A way to easily control device to stop or divert the glitter flow”. In the case that something does go wrong, being able to rapidly halt the flow of glitter could reduce the risk to both operator and other components on the production line.

Working Design Concept

The latest increment successfully accomplished a select few customer requirements. Firstly, being able to mount onto Integrity's conveyor successfully, allowing the conveyor belt to pass through the 7.5-inch inlet and exit holes. Next, the team was able to successfully control the amount of powder fed into the chamber successfully by rotating a gumball like dispenser inside of the hopper that will drop roughly one teaspoon of particles into the chamber per every rotation. In the figure below, this is a perspective from underneath the coating chamber showing that the gumball deposition mechanism deposits approximately one teaspoon of glitter into the chamber.

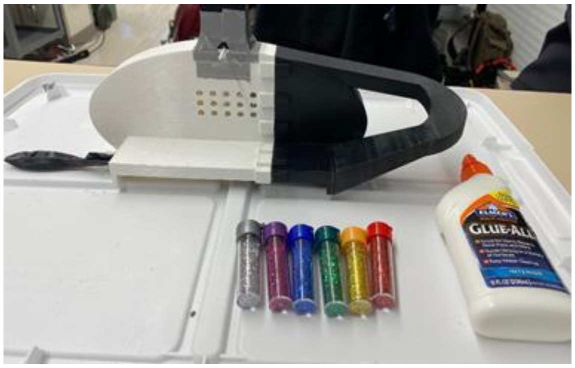

Figure 1: Glitter Box 3D Print Prototype

The team is still working on some other requirements that are not yet functioning as intended. For example, in Figure 1, air vent holes can be seen on the side of the chamber, these holes are there to balance the pressure inside the box by letting air escape while air is being pumped into the chamber. The smaller particles tend to fly out of these holes and an alternative method of relieving pressure will need to be developed. Another work in progress is the air inlet on the side of the conveyor exit, it is not shaped very well and needs to be redesigned to allow multiple different types of nozzles/inlets to attach to the system.

Figure 2: Vision from the Bottom of the Design

When adapting the Solidworks model to the current 3D printed increment shown above, multiple steps were taken to ensure client satisfaction. The chamber was lengthened so the inlet and outlet at the bottom of the design was measured to be both 7.5 inches long so the conveyer could smoothly operate under the device. The width of the chamber itself was made skinnier to take up less space on integrities conveyor. These two adjustments decreased the volume of the coating chamber. Next the air knife inlet was reformed relative to the sizing of the new skinnier design. The redistribution channel was also changed, initially, it once fed into the bottom of the chamber but was repositioned to fit into the top near the hopper in order to promote better mixing of the air flow and the particles. The hopper was decreased in size because there was no need to hold as many particles as the team had initially tried to account for. Lastly, the vent holes were made larger because there was a need to accommodate for the large influx of air entering the system. The reasoning behind the modifications made can be referenced to Key Analysis 3 where the alterations were made based off principles demonstrated in Bernoulli's Equation. The latest version of the increment can be seen below in figure 3.

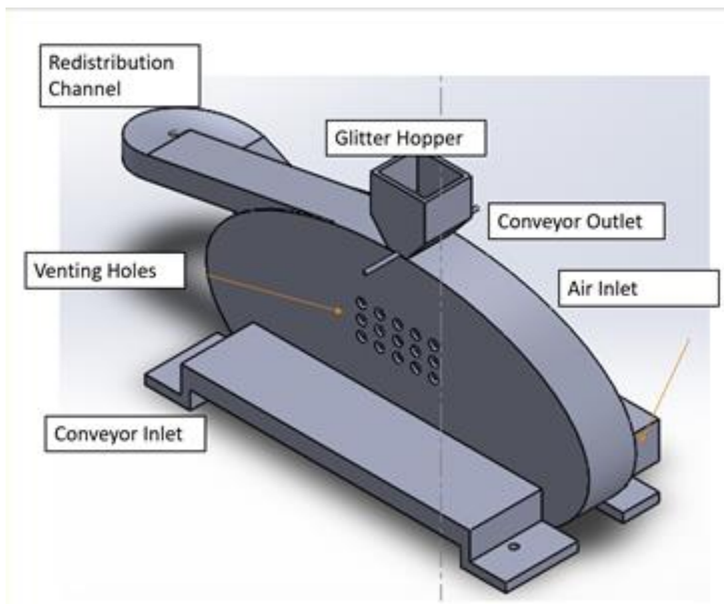

Figure 3: Solidworks Design displaying different components of the coating chamber

Analyses

Key Analyses 1: ANSYS/Fluent Simulation

As the first prototype was printing the team had already planned on making changes and producing a second. Since the first prototype hadn't finished printing yet and physical testing was limited in terms of what measurements could be made, Computational Fluid Dynamics was considered. The CFD would be used to obtain more detailed information about the flow within prototype 1 and that information would be used alongside physical testing results to make design decisions for prototype 2. ANSYS/Fluent was used to run the CFD, these programs use the continuity equation and the Navier-Stokes equation to solve for basic flow characteristics.

$$\text{Continuity: } \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0 \tag{1}$$

$$\text{Navier-Stokes: } \rho\left(\frac{dV}{dt} + v \cdot \nabla v\right) = -\nabla p + \mu \nabla^2 v + f \tag{2}$$

The SolidWorks model of prototype 1 was exported into ANSYS Workbench where a volume extraction was used to mesh the space where air would be flowing through the box.

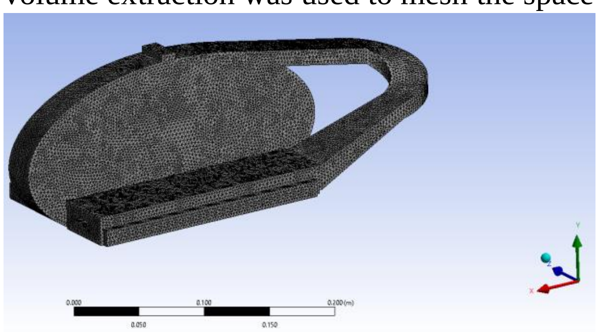

Figure 4: Interior Fluid Mesh

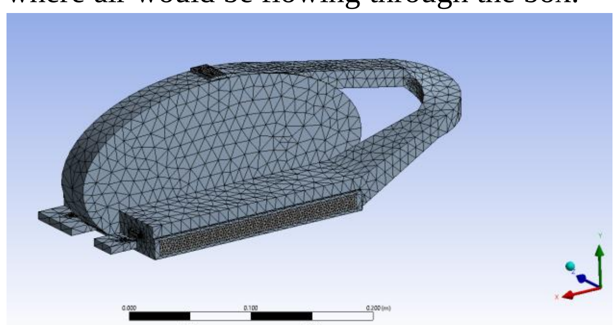

Figure 5: Exterior Solid Mesh on top of Fluid

A sphere of influence meshing method with the center located in the middle of the coating chamber was used to obtain a fine mesh of 344327 finite volumes for the interior fluid. There would be no flow through the solid, so the default coarse mesh was left untouched. This mesh was then exported to Fluent where the simulation parameters were set.

A pressure-based transient simulation was used, with gravity considered at the standard -9.8 m/s^2. The discrete phase model was enabled for the potential to inject solid particles into the flow in future simulations. Air at standard conditions of $\rho = 1.225\frac{kg}{m^3}$ and $\mu = 1.225\frac{kg}{m*s}$ was specified as the fluid to be used. The air blade inlet was specified as a velocity inlet with a velocity magnitude of $100\ \frac{m}{s}$ normal to the boundary. Both the velocity magnitude and direction of the inlet may be altered in future simulations to explore how different inlet velocities and angles change the flow within the box. All other boundaries were designated as pressure outlets into atmospheric conditions and the solid box was designated as a wall. The simulation was then initialized and ran for a total flow time of 5 seconds with a time step of 0.1 seconds. 100 iterations were run per time step to ensure simulation convergence.

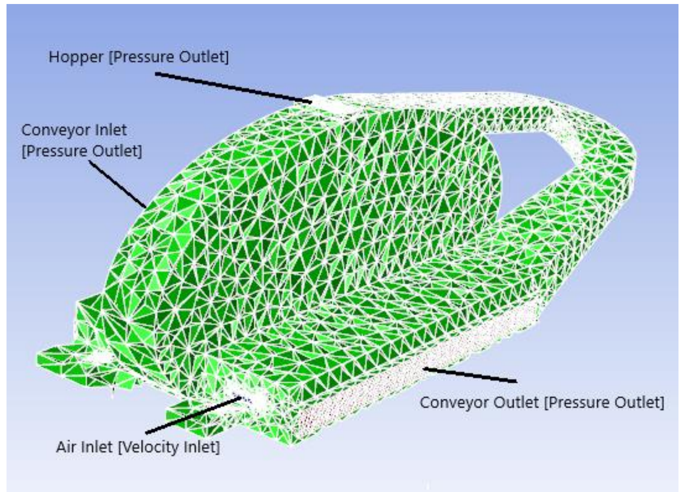

Figure 6: Labeled boundary conditions

After the 5 seconds of flow time were finished running, the data was exported to Tec Plot for formatting and analysis. The main results of the simulation were animations of velocity contours in the X, Y, and Z directions. These animations allowed the group to get a more detailed view of the flow within the box and to better understand what changes needed to be made for the next prototype. The X-velocity and Y-velocity animations showed the group that air was flowing as anticipated. The flow entered through the inlet and swept across the conveyor outlet, then it followed the redistribution channel before swirling around the coating chamber. This confirmed that the group's initial guess on how the air would flow was correct.

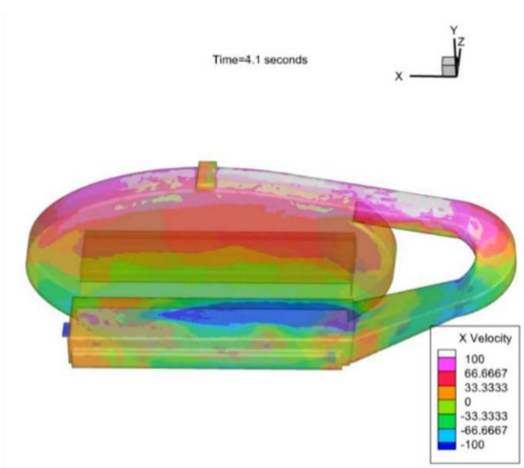

Figure 7:X-Velocity contour at t=4.1 seconds

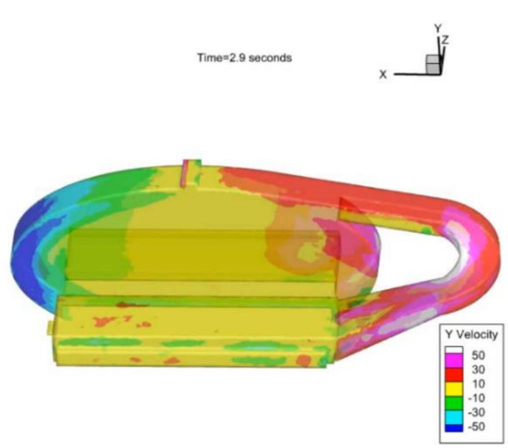

Figure 8: Y-velocity contour at t=2.9 seconds

One issue was noticed within the X-velocity animation once streamlines were implemented. As the flow progressed, areas of interference were noticed within the flow. Particularly at the base of the redistribution channel and at the right end of the coating chamber. Patches of air flowing opposite to the intended direction created spirals that disturbed the flow. Interference in the flow within the chamber could lead to potential issues with coating in the future.

In addition to the flow interference noticed in the X-velocity contour, another potential issue was noticed in the Z-velocity contour. Throughout the entire 5 second simulation there was a significant amount of airflow directed towards the conveyor outlet. This flow could carry glitter out of the box instead of directing it back into the coating chamber. As containing the glitter within the box is a high-level customer requirement, fixing this became a priority.

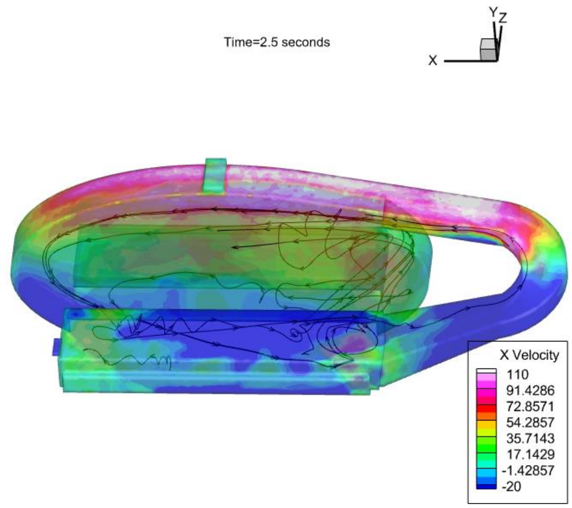

Figure 9: X-velocity streamlines at t=2.5 seconds

Both the issue shown by the streamlines and the issue shown by the Z-velocity contour could be detrimental to the project, addressing these issues became a high priority for prototype 2. The group came up with two broad solutions to both issues, the first being, changing the way air is being added to the box. This could be in the form of adding an air curtain to the conveyor outlet to prevent outflow, or perhaps changing the air inlet to blow with less force across a wider area. This solution caters nicely to CFD resources, as adding an air curtain or changing properties of the inlet is very easy to do computationally. The second conceptual solution is to change the geometry of the box to prevent these issues from occurring. This solution would take additional time as a new SolidWorks model would need to be conceptualized and subsequently modeled. However, the group is already planning on producing a second SolidWorks model which will be put through a similar CFD simulation to compare to the first prototype. Moving forward, SolidWorks modeling and additional CFD will be used in tandem to determine the most desirable characteristics for the second prototype. As the team moves into the second semester of the SEED program additional simulations will be run to gain additional

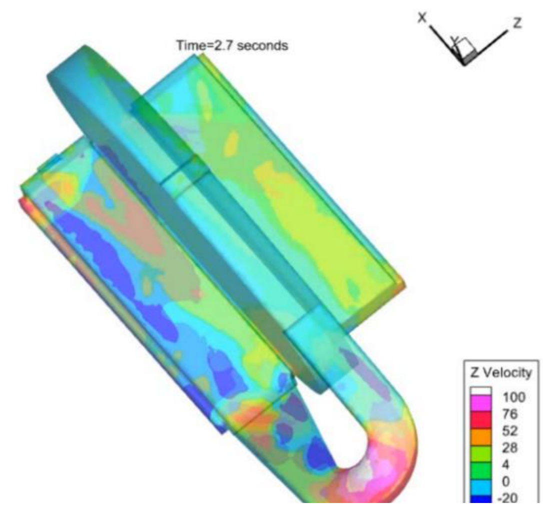

Figure 10: Z-velocity contour at t=2.7 seconds

information on the flow, this includes injecting particles into the flow via the hopper boundary layer to see how the box will act in a situation that more closely parallels reality.

Key Analysis 2: Nozzle Analysis

To achieve the requirements that glitter covers the adhesive efficiently, it is important to make sure to have a steady laminar air flow to make the glitter circulate inside of the prototype. Due to the latest testing showed the issue that the air pump wasn't able to provide the air flow strong enough to make the glitter circulated inside the glitter box, the team purchased Craftsman air pump which provides faster velocity and higher pressure of the air flow. The equipment came with multiple nozzles and each of them has different shapes. It is important to analyze the nozzle shapes and functionalities to choose the best fit for the prototype testing. From the previous testing, the team has tried the cleaner with thin long tube as nozzle, and mattress air pump with short cylindrical shaped nozzle, each of the nozzles performed differently while running the testing. It shows significant difference in air mass flow rate and pressure gradient inside the glitter box design.

To compute the mass flow rate of air, here is the theoretical equation for nozzle.

Nozzle Mass Flow Rate[1]- $\dot{m} = \rho \cdot \dot{V} = \rho \cdot \mathbf{v} \cdot \mathbf{A} = \mathbf{j}_{\mathrm{m}} \cdot \mathbf{A}$

---> $v = \dot{M}/\rho A$

ρ= density (STP: 1.225kg/m^3)

A= cross sectional area (m^2)

v= velocity (m/s)

By knowing the mass flow rate of different types of nozzles, it enables to choose the best one for the nozzle needed. As the equation above, the smaller cross-sectional area, the higher air velocity.

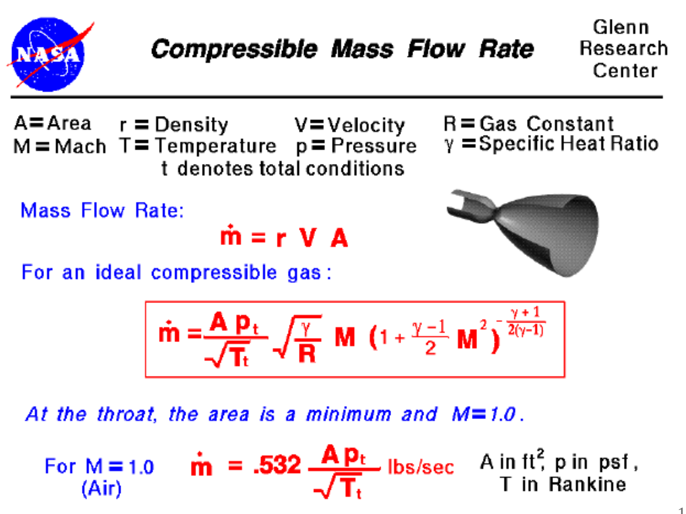

Figure 11: Nozzle Analysis: Compressible Mass Flow Rate

[1] Sourced from NASA website: https://www.grc.nasa.gov/www/k-12/rocket/nozzle.html

To analyze the air velocity and pressure provided by the nozzle, fluid mechanics theory knowledge is used here to explain the velocity and pressure gradient of the air flow in the nozzle. As the figure shown below, assuming a fully developed flow is provided by the purchased air pump and added to the glitter box, according to fluid mechanics theory, here are four types of nozzle model as options to analyze. In the first stage, it is the type of nozzle that has straight cylindrical shape. The velocity gradient of the air flow is zero, which means the air flow speed is constant. The pressure gradient is a negative constant, which means it is linearly decreasing. For the nozzle type two, it is a stage with the decreasing cross-sectional area. The pressure is decreasing while velocity is increasing. In stage 3, it reaches the minimum cross-sectional area, pressure value gets to the minimum while velocity value gets to the maximum. In stage 4, cross-sectional area increases, pressure value increases while velocity value decreases.

In conclusion, the theory above shows that the long hollow cone shaped nozzle provides the highest velocity and that is the type of nozzle which applies the best for the increment.

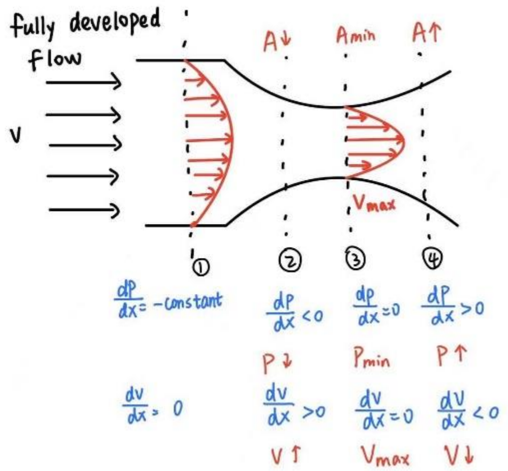

Figure 12: Nozzle Analysis: Velocity & Pressure Analysis

Figures shown below are the nozzles applied to the design during testing. The figure # on the left was about the nozzles applied at the beginning of the testing procedure. The nozzles match with the first pump used for the testing, since pump power wasn't able to provide strong enough air flow, the team changed device, however, the nozzle on the right of the figure # happened to provide the fastest air flow rate, which proved the fluid theory above. The nozzle in figure # is the one matches with the Craftsman air pump, which enables the glitter to circulate inside the glitter box successfully. The nozzle analysis helps give a perspective for improving a better laminar air flow inside the glitter box design. On the other hand, it provides the team with another direction to develop the increment in the next step.

Figure 13: Nozzles for Testing (pump 1)

Figure 14: Nozzles for Testing 2 (Pump 2 Craftsman)

Key Analysis 3: Product Development

The structure of the prototype evolved after speaking with both clients and Dr. Marshall. They offered input that would benefit the functionality of the device. After the first Solidworks design as seen in Figure 15, the team was able to see what needed to be altered.

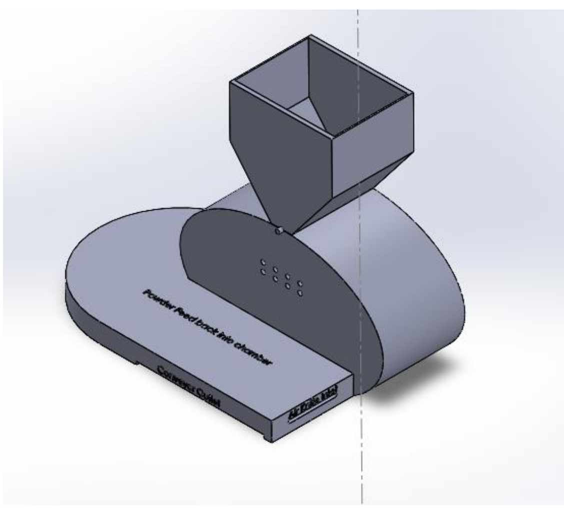

Figure 15: Orthographic View of Design 1

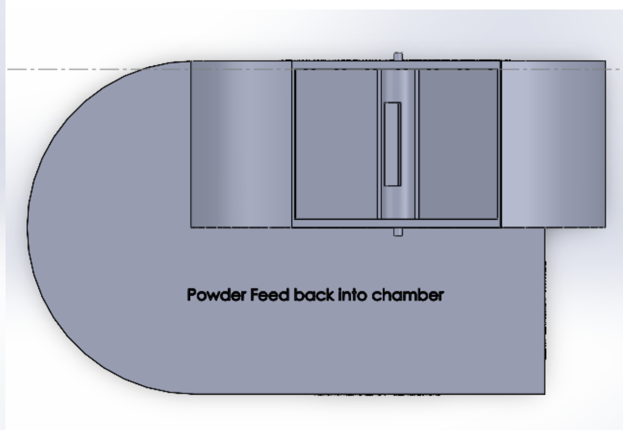

Figure 16: Top View of Design 1

In Design 1, the team included key features. With the exact measurement of the conveyer belt provided by our client, the group formatted its length and the orientation of the design so it would apply the glitter correctly to any material passing underneath. Next, the 'gumball' dropper was designed with an airtight seal, so no glitter could escape from the top when it is rotating through, scooping the glitter, and then dropping it. The deposition chamber is designed to hold a large volume, so the refill process requires less maintenance. With the addition of an air knife, the powder can be fed back into the system. This allows for little to no glitter to escape. Lastly, because the team implemented compressed air into the system, there needs to be points of pressure release. If this is not accomplished, the air will not circulate, and it will try to escape with enough force. This would lead to many issues because the air, as well as the glitter, would escape through the top where the glitter is originally deposited, or towards the seal along the conveyer belt that is supposed to be kept clear of extra particles due to the air knives. These issues are addressed with the creation of the air vents on the side, as you can see in Figure 18. These holes on each side of the design relieve the pressure, without the glitter escaping through.

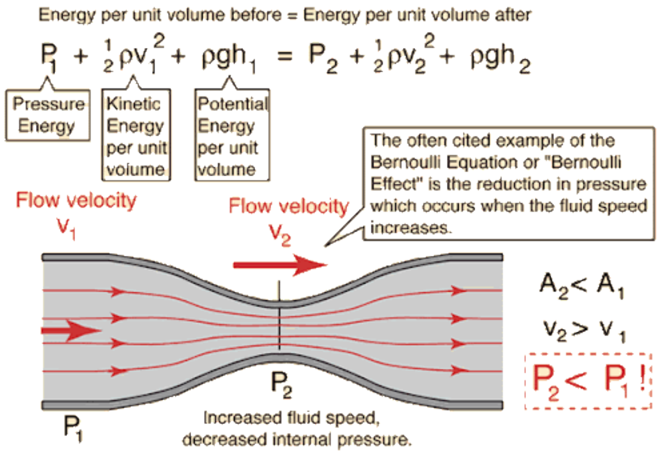

Figure 17: Demonstration of Bernoulli's Equation

Using the kinematic form of Bernoulli's Equation and the concepts supporting it, a more detailed analysis of the module was conducted. Dr. Marshall is well acquainted with fluid mechanics and gathered insights for the team to delve into. Figure 17 shows a basic demonstration of the principle. As velocity of a fluid in motion increases, in this case air, the pressure within the moving fluid decreases.

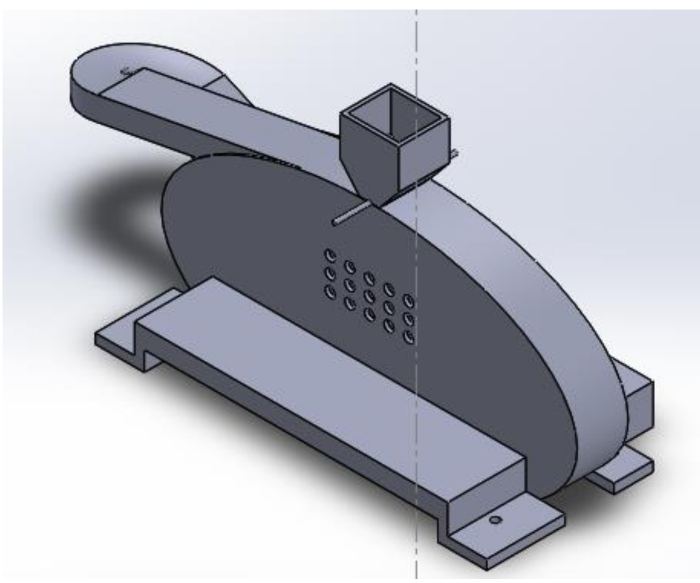

Figure 18: Orthographic View of Design 2

With a better understanding, new revisions were made to the Solidworks design. At the top of the design, the changes included reducing the hopper size and reducing the chamber size. The group found it unnecessary to have such a large hopper. Minimizing the size allowed for less chance of error with glitter escaping. The goal of lengthening and decreasing the size of the chamber was to alter the direction of the air flow once it entered the chamber and started to circulate. This would potentially help with redirecting the recirculating flow so it may create turbulence. Changing the geometry of the design has drastic effects on the streamline of the air flow, something the group is still discovering and experimenting with. Other alterations involved reducing the air knife inlet so there is less of a gap for glitter to escape from. Creating a tunnel at the inlet allows for a more directed flow instead of just a slit seen in Design 1. The group found that there was a need for more pressure relief, so the vent size was increased on each side to stabilize the pressure equilibrium. It is necessary to apply positive or neutral pressure within the system because the conveyer belt system does not operate well with any vacuum or negative pressure. Lastly, mounting holes were added so the product could be attached to the conveyer belt system at Integrity.

After testing in Sprint 3, the team found it was necessary to consider other ways to manipulate the air flow within the chamber so the glitter particles can be swept up and circulated. After analyzing the pattern of the flow and using the principles of Bernoulli's Equation in Figure 17, developing a better understanding of pressure, some alterations have been theorized that will increase the performance of the device. First, the size of the inlet would be increased. It currently has a small entry where high velocity enters the device and is driven into a low-pressure unit. It is desirable to create a laminar flow before or as it enters the device so that the pattern of the streamlines is more direct. The 180° turn consists of a narrow channel. It is already difficult to change the direction of air flow, and for it to be directed towards a high-pressure area is even more difficult because the fluid is attracted to low pressure. In this current setup, turbulence is the result. Widening or enlarging that channel in general will decrease turbulence. Lastly, the team is proud of the results coming from the hopper and gumball deposition design, but there are plans to advance it. The new adaptation would involve a more gradual deposit of the glitter, instead of scooping once and dumping all the glitter. This is being done for multiple reasons. First, it would make the glitter deposition more consistent and be less glitter dumping at once, but more frequently. Next, it is much more feasible to carry a particle in the air when it is more scattered compared to being a part of a large clump.

Key Analysis 4: Particle Sizing and Settling Rate

The process of finding out how to make the design work has proven to be challenging, however there are certain ways that it works better than others. For example, what works the best so far is using larger particle sizes that do not weigh very much at all, meanwhile what works the worst is using small particles that weigh more. It was not very easy to get to these small particles to blow around. At first this concept made sense because but there was no research done showing how particle size might affect our design, the team wasn't able to fully grasp why these smaller particles weren't mimicking the larger ones. This prompted an expansion of research to begin. After speaking with Professor Marshall about the project he suggested investigating the settling rate of the particles. At this point, quite a bit of testing had been done and the team learned a lot about the project, but it wasn't until the research began on how the settling rate may affect the flow of the particles that the team realized how vital this sort of analysis is for the project. The door has now been opened to understanding the results that the testing is producing. In the figure below, figure 19 the equation for the settling velocity of particles is shown along with its parameters and what each one means listed in the figure.

Equation 10.1: Stoke's Law for settling solids (Stokes 1851)

$$V = \frac{g\left(\rho_1/\rho - 1\right)d^2}{18\upsilon}$$

where:
V = settling velocity of the solid
g = acceleration of gravity
ρ_1 = mass density of the solid
ρ = mass density of the fluid
d = diameter of the solid (assuming spherical)
υ = kinematic viscosity of the fluid

Figure 19: Settling Velocity

The settling velocity of the particles shows how quickly a particle will fall to the ground. Essentially it is an equation that determines the terminal velocity of a particle and is useful because there is a direct correlation between the settling rate and how easily the particles can be blown around in an air flow. The only factors that will actively change from equation 10.1 are the mass density and diameter of the solids during the interchange of the different particle sizes. The rest of the parameters will stay constant because this device will always run at the same atmospheric pressure, and gravity will never change.

After understanding the concept of the particle settling rate the team was able to run another series of tests using four different particle sizes to further understand the theory of the settling velocities. Large paper particles, medium size plastic particles, and glitter particles that came in small and tiny sizes were used during these tests, they can each be seen in the following image, figure 20.

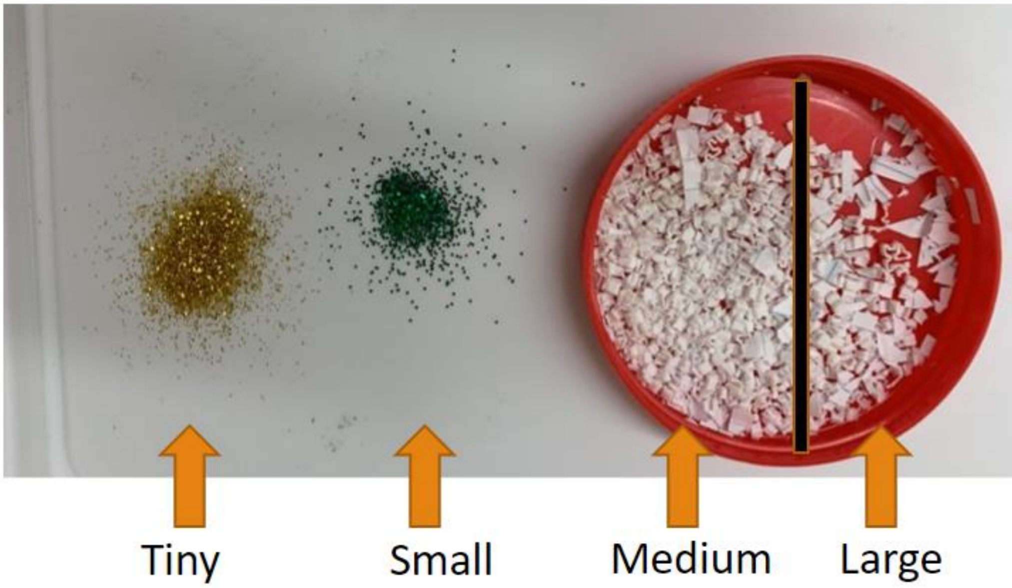

Figure 20: Displaying different particle sizes

When using a compressed air can as the source for each particle size, each particle reacted differently relative to one another. The large particles successfully traveled through the coating chamber, flowing through the correct path with very few flowing the wrong way. Firstly, this is because the air in the system tends to flow similarly to the way that the team intended, secondly, because the density of paper is very low, and the diameter of the paper particles is larger, so the flow can easily lift and blow the paper particles along the path the flow is already moving. The medium plastic particles had a smaller diameter than the large ones, and a higher density, so not many of them were able to flow along the correct path as easily. The small and tiny glitter particles both had approximately the same density as the plastic but had a much smaller diameter, so these particles were the most difficult to blow around and very few managed to flow along the correct path. This explains why the large paper particles were the only ones to successfully flow through the chamber, and why the three smaller particle sizes, glitter, and plastic, failed, and only had very few particles that were able to successfully flow through the chamber. The results are very interesting because it shows that the compressed air can was unable to produce a flow strong enough to blow some particles, however, was strong enough to move some.