Design of Particle Capture System for $PM_{2.5}$ on a Rover

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Abstract

$PM_{2.5}$ is a harmful particle found in the atmosphere in dangerous quantities in certain areas of East Asia. The MPD team, Mapleseed, has multiple projects working in tandem to address needs in data collection from the atmosphere. One of these projects is a drone which seeks to analyze the concentration of $PM_{2.5}$ as well as other particles within atmospheres to provide insight on danger levels to the citizens. Currently, no inexpensive technologies exist to address this need, especially in regions of the world where $PM_{2.5}$ is a considerable threat to the people. On a larger scale, the COVID-19 Pandemic has brought upon a significant rise in awareness for the dangers of certain particles in the air. This project seeks to take a step forward in addressing this concern.

The purpose of this project is to bolster the drone's particle collection system. This is largely done through the implementation of an air pump in order to increase the efficiency of collecting the particles into the location where the microscope can analyze the particles. In order to simplify the scope of work, the implementation was conducted on a rover instead of a drone, but with the same microscope system. The results show an increase in particle collection, with potential consequences on the ability for the drone to maneuver. Further analysis of particle flow through programs such as COMSOL, microscope stabilization, and implementation onto a drone will be done in future work.

Introduction

The COVID-19 Pandemic has increased the necessity for understanding the potential danger of particles in the air. While new methods for gathering biological samples for testing have been developed to better inform the public on the spread of COVID-19, the dangers of particles in the air extend to larger contexts, and more research must be done to properly protect the wellbeing of communities. Within the 14 Grand Challenges for Engineering, the study relevant to this project is encompassed by the challenge to *Advance Health Informatics*. The challenge lists a necessity of technology to analyze particle concentration, and the importance of pandemic preparedness.

For the scope of this project, Fine Particulate Matter ($PM_{2.5}$) has been studied. $PM_{2.5}$ is a category of particles which include all fine particles that are 2.5 microns (10^{-6} m) in diameter or smaller. Particles classified in this way have been shown to affect lung function when inhaled, and can worsen many medical conditions. Heightened levels of concentration of $PM_{2.5}$ in atmospheres have increased rates of hospital admissions and can severely impact immunocompromised people, elderly, and children. Long-term exposure to $PM_{2.5}$ has also been linked to premature death. Data collection and research of $PM_{2.5}$ have been prevalent for decades, however there has been a noticeable gap of development in inexpensive methods for its collection.

The goal of this project is to develop a method of collecting particles in atmospheres by utilizing a motorized device, such as a drone or rover. Through the exploration of particle collection measures, this project aims to increase the rate and concentration of fine particles to be examined.

Previous Progress

The University of Michigan hosts a research initiative named the Multidisciplinary Design Program (MDP), geared toward allowing students from different disciplines to collaborate to create more innovative and diverse solutions to existing problems. One group within this program, named Mapleseed, has worked on projects involving drones and wireless sensors for data collection. A drone armed with particle collection mechanisms has been in the rotation of projects of this team in past semesters, and I have contributed to its development in past semesters. This drone utilized a microscope which can capture images of particles in real time, and machine learning work has been done to allow for analysis of these particles. The drone, with a funnel as its particle collection method, can be seen in Figure 1 below.

Figure 1. Mapleseed's particle collection drone, with a funnel attached to collect particles.

By taking this drone into consideration and internalizing the progress made by past teams, a clearer image for this project's goals can be visualized. With the funnel design not yielding strong results for particle collection, the goal of this project is to improve the drone's ability to collect particles in the air for analysis. The four quantifiable goals for this project are as follows: more effective than previous efforts, easy to operate, easy to integrate, and inexpensive.

Due to the inaccessibility of the drone shown above, a rover was provided instead. The rover includes the same microscope system as the drone, but with different mating designs for their respective use cases. While both a drone and a rover provide mobility for particle collection to occur in various locations, future considerations will be necessary to adapt any design across the two devices. The rover can be seen in Figure 2 on page 3 below.

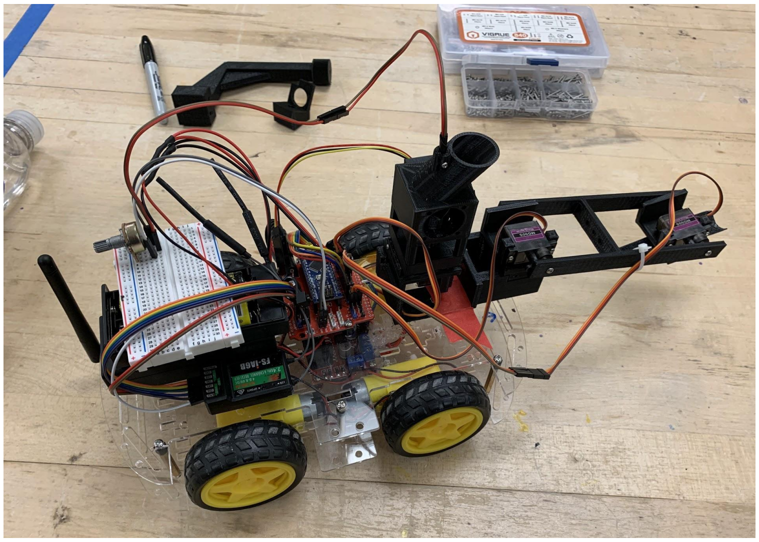
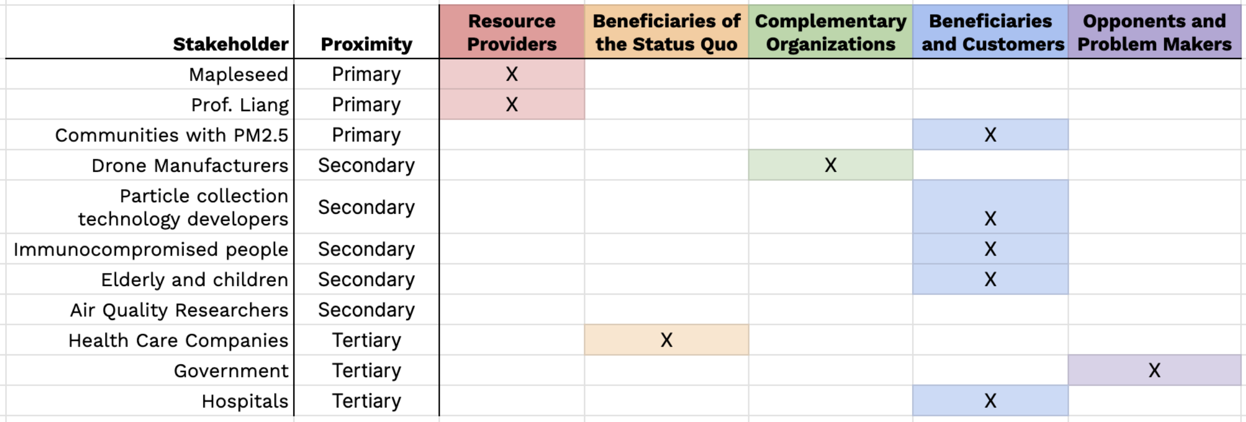


Figure 2. The particle collection rover that was provided for this project. The microscope assembly is the same as the drone. The rover was originally used as an ENGR100 section's project.

Stakeholder Map

With past progress accounted for, research was conducted to construct a stakeholder map. The stakeholders were all identified by their proximity to the issue, as well as their classification. The classifications include resource providers, beneficiaries of the status quo, complementary organizations, beneficiaries and customers, and opponents and problem makers. This map can be seen in Table 1 below.

Table 1. A stakeholder map, including the proximity to the problem at hand, as well as their classification.



Stakeholder	Proximity	Resource Providers	Beneficiaries of the Status Quo	Complementary Organizations	Beneficiaries and Customers	Opponents and Problem Makers
Mapleseed	Primary	X				
Prof. Liang	Primary	X				
Communities with PM2.5	Primary				X	
Drone Manufacturers	Secondary			X		
Particle collection technology developers	Secondary				X	
Immunocompromised people	Secondary				X	
Elderly and children	Secondary				X	
Air Quality Researchers	Secondary					
Health Care Companies	Tertiary		X			
Government	Tertiary					X
Hospitals	Tertiary				X	

The primary stakeholders are the ones that were primarily considered during the decision making process of this project. Mapleseed, the MDP team, provided the previous progress that heavily informed the start points of this project. Professor Xiaogan Liang provided all necessary materials and assisted through consistent meetings to address any concerns that were brought up. Communities with $PM_{2.5}$ prevalence were considered as they were the most prominent customer of the results of this project.

Requirements and Specifications

With a better understanding of the necessary considerations for the remainder of this project, the requirements and specifications for a suitable solution were developed. Table 2 below displays all of the requirements and their respective specifications. The most important requirements are at the top of the table, with the importance of each decrease toward the bottom.

Table 2. A table with all of the requirements and specifications for the project. The requirements are listed in order of importance, with effective being the most important.

Requirements	Specifications
Effective	● Collects maximum particles in minimum time frame ● Creates an airtight seal for any collection mechanism
Non-Impeding	● Does not alter the device's movement by more than 10% ● Does not require power from device's power source
Easy to Integrate	● Can be integrated into different devices ● Can be built/attached with a maximum of 2 tools
Inexpensive	● Total cost should be below $40
Easy to Operate	● Does not add complex operating mechanism ● People with minimal technical background can operate intuitively

Effective. The most important requirement of the particle collection design is its ability to effectively collect particles. This requirement is broken down into two specifications: its ability to collect particles within a time frame, and its ability to maximize the amount of particles that flow through. This requirement will be heavily taken into consideration for all design decisions.

Non-Impeding. Due to the fact that the collection mechanism must reside on a device such as a drone or a rover, the design must not impede on the device's ability to maneuver. Additionally, it would be a strong added benefit to consider methods that do not require power from the device.

Easy to Integrate. Since this design must be adapted between devices (namely a drone and a rover), it is important that it is easy to integrate. It should not require fixtures that are permanent or can only be utilized with one device. It must also be installed with a maximum of 2 tools.

Inexpensive. With one aim of this project being accessibility of the technology, the entire design must be inexpensive. Impacted communities may not have access to sufficient funds, so the price should be kept to a minimum. The estimated cost with affordability in mind is $40.

Easy to Operate. Since this design will be a part of an already complex device, the added particle collection mechanism should be easy to operate. With impacted communities in mind as a possible use case, the operation of the device should not require a technical background.

Concept Generation

Now that we are equipped with suitable requirements and specifications, brainstorming can follow to provide options for moving forward. The process for which concepts were generated and screened can be seen below.

Benchmarking. As stated in the introduction, many studies have already been done regarding particle collection, and thus technologies already exist for the collection of particles. Research was done into the various existing methods, and four main ideas were chiefly considered. These ideas are a funnel, an air pump, the usage of adhesives, and liquid collection.

A funnel can quickly come to mind as a way to encourage particles to reside in a reservoir. The primary benefit of a funnel is its ability to provide a wide range for particle collection. While the main use case of a funnel involves liquids, solids can also be moved with additional help. Since the use of a funnel mostly relies on gravity or an external force to guide matter through it, a funnel by itself would not sufficiently serve our purpose. In previous progress by Mapleseed, a funnel design was utilized and operated successfully with the added movement of the drone itself. With the funnel facing outward, the movement of the drone can 'collect' the particles. This funnel design can be seen in Figure 1 on page 2. In addition to this drawback, the material selection of the funnel requires consideration due to the fact that surface roughness can invite decreased efficiency in the form of particles sticking to the funnel.

An air pump is a way for particles to be forced to flow, and can provide very high efficiency while doing so. Usually, a switch is turned on which starts up a motor to create airflow within the pump. Many air pumps are very large, so space concerns will definitely be highly considered. Due to any design needing to fit onto a drone or a rover, most air pumps would likely be disqualified immediately. In addition, air pumps will likely be expensive.

Adhesives are also an existing method for particle collection. In general, adhesives such as tape or petroleum jelly are applied to a fixture, and particles stick onto the adhesive over time, or as a result of some sort of movement. This method requires no mechanical energy and can be a strong option for long term collection of particles. However, the methods required to remove the particles from the adhesives for studying would most likely be difficult to implement.

Liquid collection is a very prominent method used for collecting particles. A liquid droplet is placed in the path of the gas streamlines which the particles are carried by. The particles interact with the liquid and remain inside of it, making them effectively 'captured' in the liquid. For the scope of this project, this method may lead to losses in the microscope's analysis capabilities, as the current design does not account for any type of liquid. With liquid being required for every sample to be collected, it must also be removed before the next trial. Ejection mechanisms do exist, but the introduction of liquid would likely complicate things and may necessitate human input between trials. This method is likely to be more difficult to integrate, and can lead to higher costs as well.

Pugh Chart Analysis. After the four general ideas were put into consideration, they were screened by comparing them against each other. The comparisons were done through the usage of a Pugh Chart. The Pugh Chart included the requirements that were listed earlier, with relative weights for each requirement, and a rating for how each idea performs the requirement. This Pugh Chart can be seen in Table 3 below.

Table 3. A Pugh Chart to compare the performance of the four main ideas against each other. The project requirements are listed on the left, with their respective importance values ranging from 1 to 10. Each idea was given a rating ranging from 0 to 4 for each requirement based on their predicted performance of each requirement's specifications. A total value was computed for each idea, and a relative total was calculated.

		Funnel		**Air Pump**		**Adhesive**		**Liquid**		
Requirement	**Importance**	*Rating*	*W. Total*	*Rating*	*W. Total*	*Rating*	*W. Total*	*Rating*	*W. Total*	4 = very good (ideal)
Effective	10	1	10	4	40	0	0	3	30	3 = good
Non-Impeding	8	3	24	2	16	4	32	4	32	2 = adequate
Easy to Integrate	7	4	28	3	21	4	28	1	7	1 = just tolerable
Inexpensive	5	4	20	2	10	4	20	3	15	0 = unsatisfactory
Easy to Operate	5	4	20	4	20	4	20	2	10	
Total (out of 35 x 4 = 140)	35		102		107		100		94	
Relative Total (div by 140)			**0.73**		**0.76**		**0.71**		**0.67**	

Each rating was assigned based on engineering intuition as well as research on each method's performances in other contexts. The relative totals show that the four methods would perform relatively similarly, however upon closer inspection it can be seen that the air pump holistically outperforms the other methods. The air pump has a rating of 4 for Effective, the most important requirement, while the funnel and adhesive have a rating of 1 and 0 respectively. While the totals are similar, the most important requirement is only met by the air pump, out of the top three contenders. For these reasons, the air pump was selected as the idea to move forward with.

Air Pump. With a wide selection of existing air pumps to choose from, research was conducted to determine an optimal option. The main considerations for this selection included the price point, weight, battery capacity, and ease of use. After several options were considered, the FLEXTAIL GEAR MAX PUMP 2020 was ultimately selected for fulfilling each of the considerations listed above. This air pump can be seen in Figure 3 below.

Figure 3. The FLEXTAIL GEAR MAX PUMP 2020, the air pump selected for this project.

The price for the air pump was $28.99 when purchased, and the specifications listed 0.33 lbs as the weight, 2.2 kPa as air pressure, and 300 L/min as wind speed. The price point was low enough to fit within the specification, and the weight does not immediately bring up concerns for inhibiting design decisions in the future. The air pressure and wind speed are sufficient for the applications of this project. Additionally, the operation is simply done by moving a switch on one of the sides, and is small enough to fit onto the chassis of a drone or rover in many configurations. As an added bonus, the air pump comes with many inlet and outlet adapters which can be used in builds to allow for more reliable and airtight connections between parts.

Alpha Design

With the air pump selected, it had to be implemented to the rover's microscope assembly. The microscope assembly being used for this project includes a housing part, a concentrator, the microscope, and a base plate. The microscope assembly can be seen in Figure 4 below.

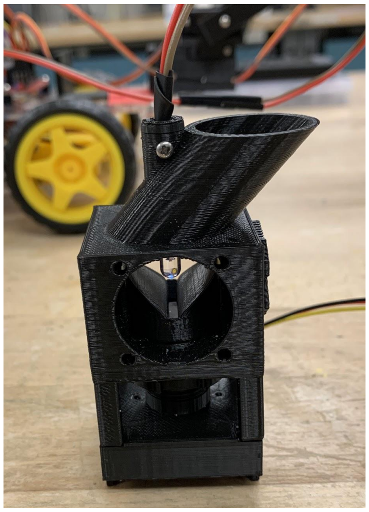


Figure 4. The microscope assembly being used for the rover and drone. The assembly includes a housing at the top with an inlet and ejection holes, a concentrator to guide the particles into the proper place, the microscope itself, and a base plate that interfaces with the rover.

Considering the general shape of this assembly, the air pump would likely perform best with some sort of tubing, providing space between the pump itself and the microscope. This would provide flexibility in design. With this in mind, a sketch was created to conceptualize the flow of air that the mechanism would seek to employ. This sketch can be seen in Figure 5 below.

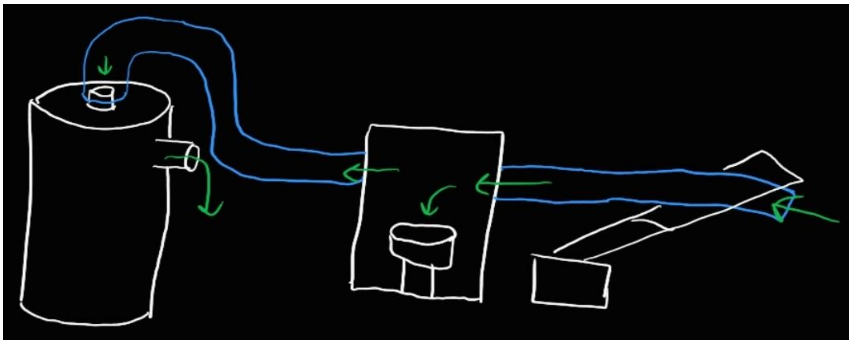
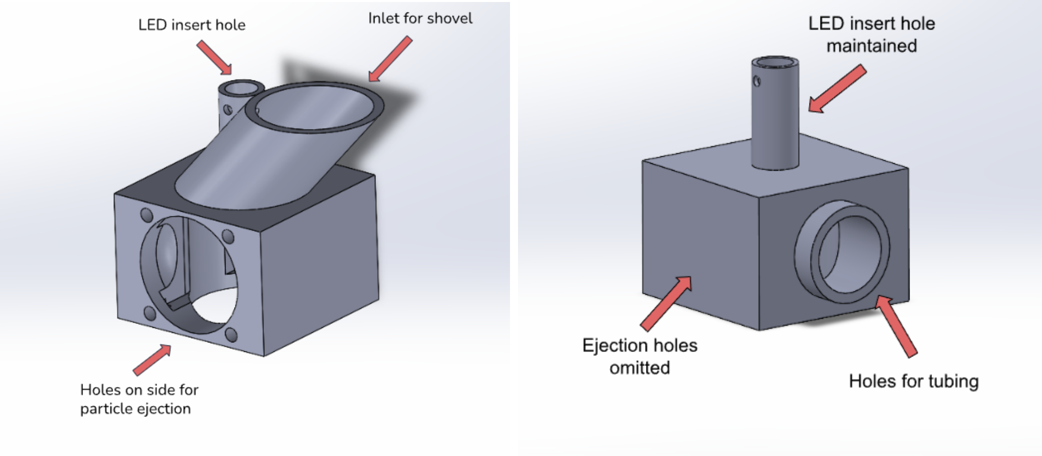


Figure 5. A baseline sketch of the mechanism, including the air pump, tubing, the microscope assembly, and the rover arm. The green arrows indicate the direction of airflow.

The air pump would be connected to tubing, which would be connected to the microscope assembly. More tubing would leave the other side of the microscope assembly, and this end of the tubing would be controlled by the rover's arm that already exists. With this general idea in mind, parts were ready to be redesigned to interface with the air pump.

Prototyping

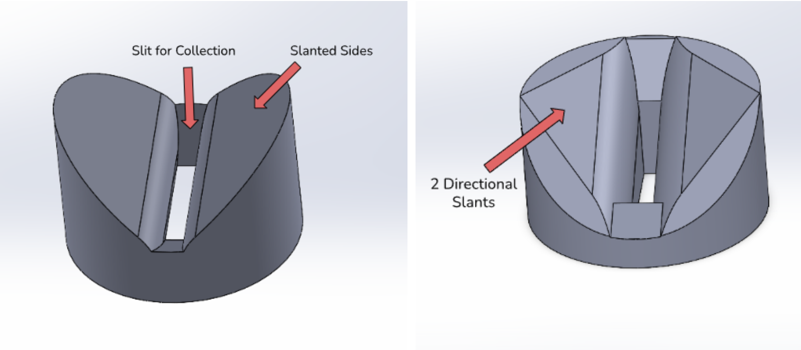
As stated above, the current microscope assembly design would prove to be difficult to incorporate an air pump and tubing. For this project, the housing and concentrator were both redesigned. The before and after images of the housing component redesign can be seen in Figures 6a and 6b respectively below.



Figures 6a, 6b. The existing design for the housing (left) and the redesign (right). The inlet and ejection holes from the existing design were omitted, and holes that interface with the tubing were added.

The main redesigns were the omission of key characteristics such as the inlet and ejection holes, as well as the addition of holes that would interface with the tubing. In order to provide a straight line for air to flow through, the inlet and outlet were made to be on opposite sides of the component. The ejection holes were omitted to create as airtight of a passageway as possible.

The other component that was redesigned was the concentrator. The purpose of the concentrator was to provide slants for particles to fall down so that they can enter a reservoir to be studied by the microscope. The before and after images for the concentrator redesign can be seen in Figures 7a and 7b respectively below.



Figures 7a, 7b. The existing design for the concentrator (left) and the redesign (right). The slants were redesigned to create two directions for particles to be able to fall from: straight ahead and from the sides.

Due to the housing being redesigned so that air would flow through the front of the design, the concentrator was changed to allow particles to be collected from the front. In addition, deviations to the side were also accounted for by the slants going off to the sides.

With these components redesigned, the prototype could be built. The above parts were 3D Printed due to its ease of manufacturing, and PLA was selected as the material due to its inexpensive yet strong nature. The printed parts can be seen in Figure 8 below. The parts were adhered to the rover using a combination of epoxy and electrical tape.

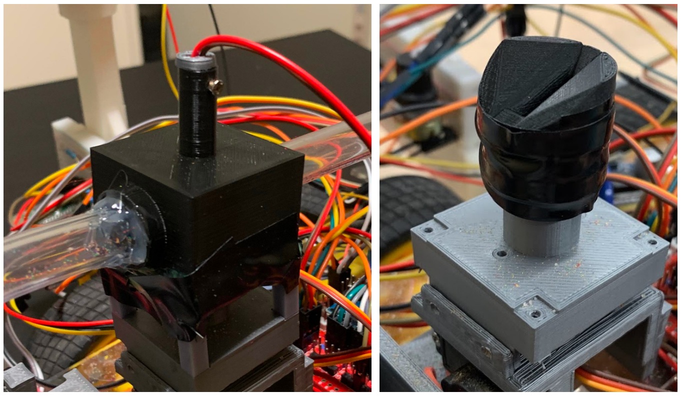


Figure 8. The 3D printed redesigns for the housing and concentrator.

When purchasing the tubing, the most malleable material was selected while being within the diameter of the holes in the housing design. The tubes were cut to their prescribed lengths and adhered to both ends of the housing with hot glue. Hot glue was selected due to its ability to provide an airtight seal. The tubing was hot glued to one of the inlet adapters provided by the air pump, and the adapter was then attached to the air pump's inlet. The completed prototype can be seen in Figure 9 below.

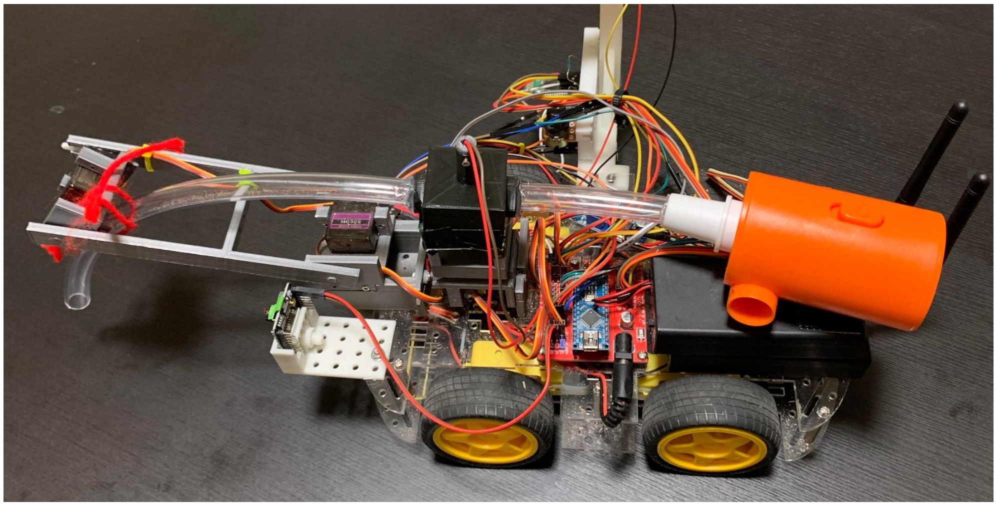


Figure 9. The completed prototype, including the air pump, tubing, microscope assembly, and the rover.

All of the tubing was kept as straight as possible, and the air pump was placed on top of the battery packs to best enforce the direction of airflow. The air pump pump was fixed to the battery pack with velcro. The tubing at the front of the rover was connected to the arm with string to provide better maneuverability of the arm.

Testing

With the prototype completed, testing was conducted. The goal of testing was to see the air pump design's performance in collecting particles. The test setup involved the prototype, two different particles for collection, the rover controller, and the microscope display. This setup can be seen in Figure 10 below.

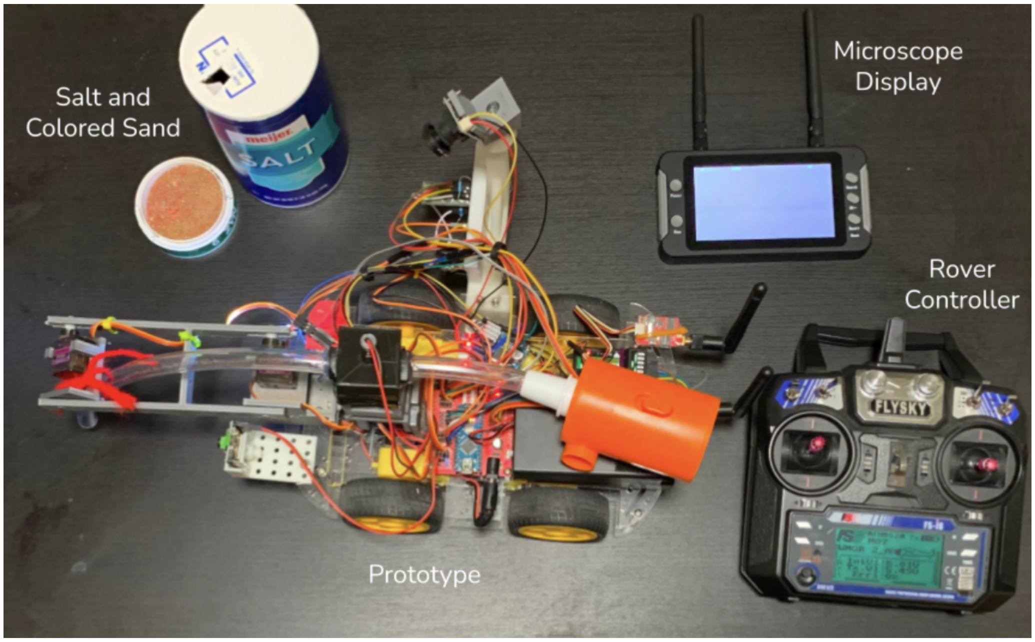


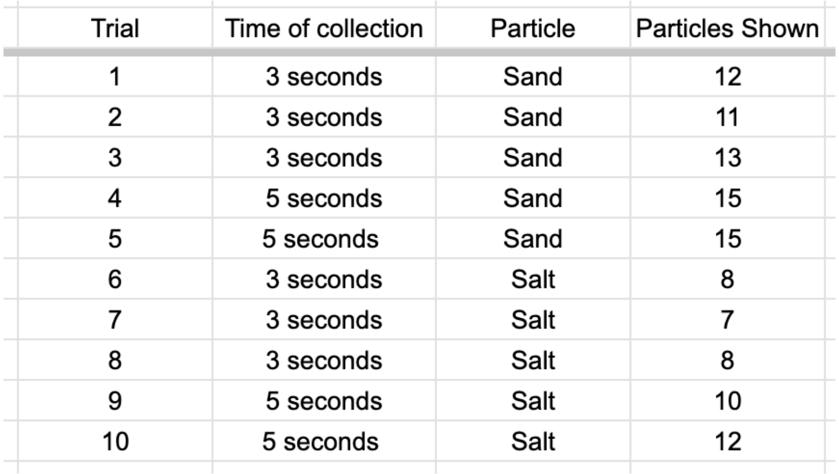
Figure 10. The test setup used for all tests. The two particles to be collected were salt and colored sand.

For each test, one of the particles was placed on a surface, and the rover and microscope would be powered on by switching their respective battery packs on. The air pump was then turned on for a prescribed period of time, and the rover controller was used to guide the tubing to the particles. Once the time period was over, the air pump was turned off, and the trial was over. At the end of the trial, the amount of particles seen on the microscope display was counted and recorded. An example of the microscope imaging can be seen in Figure 11 below.

Figure 11. The microscope display with particles present.

Due to the microscope's high resolution, counting the particles present could be done very easily. A subset of the data collected can be seen in Table 4 on page 11 below.

Table 4. A table showing some of the results of the testing conducted. Time frames of 3 seconds and 5 seconds were selected for these tests.



Trial	Time of collection	Particle	Particles Shown
1	3 seconds	Sand	12
2	3 seconds	Sand	11
3	3 seconds	Sand	13
4	5 seconds	Sand	15
5	5 seconds	Sand	15
6	3 seconds	Salt	8
7	3 seconds	Salt	7
8	3 seconds	Salt	8
9	5 seconds	Salt	10
10	5 seconds	Salt	12

The tests show a much higher collection speed with the air pump, compared to without. In trials conducted with the rover by itself, it would routinely require over 10 seconds to collect enough particles to populate the microscope display screen. With the air pump, the entire screen was consistently filled up within 5 seconds. The particle density shown in the display was also much higher than without the pump. Given the same time frame, trials without the pump collected an average of 3.5 less particles for salt, and 5 less particles for sand.

While a few conclusions were able to be drawn from the testing, many issues arose that could be addressed by future iterations of the prototype design. One such issue is the fact that the range of motion for the rover arm was severely limited by the tubing. While the tube material that was selected was the most malleable option at the store where it was purchased, it still proved to be too rigid, as the arm's range of motion was reduced by around 50%. In addition, the lack of an ejection mechanism created difficulties in conducting multiple trials in a row, due to the fact that particles would sometimes remain lodged in the microscope even after attempts to empty the cavity. Adding a proper ejection mechanism would likely provide more reliable results. Lastly, implementing better airtight seals between some of the components would likely increase the performance of the design.

With these considerations in mind, future tests should be conducted after a new prototype has been created. With future tests, different quantifying variables should also be considered. First, weight should be considered as a method of measuring the amount of particles collected. This is due to the fact that the microscope display does not completely show all of the particles that were collected, so the weight can be a more consistent measure. In addition, smaller particles should be explored for collection, since salt and sand are significantly larger in size than $PM_{2.5}$.

Future Considerations

With the initial prototype and tests providing some useful conclusions, future considerations were made. Specifically, addressing the end goal of this project: adapting this design to a drone. Due to the focus being placed on a rover for the duration of this project, much of the work to implement the design to a drone is yet to be completed. Main factors to consider for the redesign include the inhibition of movement, air flow direction, space and weight concerns, and remote pump operation.

Inhibition of Movement. With one of the goals of the air pump assembly being to not impede on the movement of the device on which it is placed, this consideration must be thought about more carefully with regards to a drone. With the drone not being supported by the normal force of surfaces, the forces created by the air pump may greatly impact the movement of the drone. Free body diagrams and calculations of forces by the air flow should be evaluated.

Air Flow Direction. A drone moves by generating lift, commanding the flow of air in its surroundings with rotors. With the air pump also needing to generate air flow, it is important that these do not interfere with each other. In addition, ideas such as the entrapment of air in the surroundings of the drone can provide easier opportunities for particles to be collected. These ideas should be considered, and COMSOL simulations should be performed to create the optimal implementation of the pump.

Space and Weight. While the current air pump is relatively lightweight, it is important to consider the fact that a drone is likely less stable than a rover. Depending on where the weight is placed, there can be significant implications on the center of gravity, and thus the drone's ability to move accurately. Weight should be removed to the largest extent possible, and counterweight measures should be considered for the stability of the drone.

Remote Pump Operation. The operation of the drone inherently requires that the drone is in the air. With the current design of the air pump, a switch must be toggled on and off to operate it. Thus, a method for the air pump to be operated remotely must be investigated.

Conclusion

Through benchmarking, concept generation, and prototyping, a design involving an air pump to increase particle collection on a rover was developed. Testing provided insights on a general increase of effectivity in this new design, however limited testing and prototype issues prevented more meaningful data from being collected. Future iterations of the design should be created, further tests should be conducted, and problems to overcome when adapting the design to a drone should be considered.