Unmanned Ground Vehicle for Foreign Object Debris Removal

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ACRP Challenge: Airport Safety, Operations, and Maintenance

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ENGINEERING LEADERSHIP DEVELOPMENT

Executive Summary

In this proposal, a team of five undergraduate engineering students in Penn State's Engineering Leadership Development program propose a solution for automating the removal of foreign object debris (FOD) on runways at airports. The proposal is based on the ACRP Design Challenge - Airport Safety, Operations, and Maintenance: Improved methods for foreign object detection and removal from runway surfaces. The team proposes the use of an unmanned ground vehicle, or UGV, that will be designed to autonomously retrieve and remove FOD from runways when incorporated with a FOD detection system. In this proposal, the team analyzes the potential impact of this solution through insight from experts, a thorough risk assessment, and an in-depth cost-benefit analysis. In accordance with their cost-benefit analysis, the team concludes that the solution is economically feasible and can provide tremendous benefits on a yearly basis to an airport. FOD is one of the most costly problems that airports face, and this UGV solution is one of the first attempts to make FOD removal automated, safer, and more effective than human removal. By using this vehicle in its designed system, airports can save millions of dollars from reduced airplane damage and maintenance costs as well as reduced costs associated with delayed flights caused by FOD. Additionally, airports can remove the liability and safety hazards associated with sending humans out on runways to remove FOD.

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Problem Statement and Background

This project's design is a proposed solution to ACRP challenge section I: Airport Safety, Operations, and Maintenance, subsection B: Improved methods for foreign object detection and removal from runway surfaces.

Nearly every commercial airport experiences the buildup of FOD on runways and operational surfaces. The process for detection, identification, and removal is often quite slow and poses a risk to the safety of workers and operationality of the airport. Ground crews have limited time for visual inspection and manual removal of FOD. Coupled with the busy and chaotic nature of communicating with air traffic control, workers understandably have a low removal rate.

According to an analysis done by Boeing, FOD is estimated to cost the aviation industry four billion dollars annually[1]. This comes in direct costs associated with damages to airplanes, airport property, and worker's compensation, alongside indirect costs such as delayed or canceled flights, and maintenance and upkeep costs.

Overall, FOD has become a significant issue to the aviation industry and demands a new innovation to reduce costs, and increase safety.

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[1] *FOD Management Program.* (n.d.). Los Angeles World Airports. https://www.lawa.org/groups-and-divisions/airport-operations/programs/fod#:~:text=An%20analysis%20by%20Boeing%20(cited,aircraft%20out%20of%20service%20time)

Summary of Research

Literature Review

Much of our initial research focused on the use of drones for FOD detection. The literature we reviewed showed what airports are doing to be drone-ready and also exposes the drones' possible applications in airport systems. Drones give an economical and high-resolution imaging alternative to manned aircraft, handy for aerial views close to the ground and around trees and buildings as jamming obstacles. Nevertheless, the application of UAVs for small-scale topographical investigations is limited since their legal flight ceiling is only 400 feet, which makes continuous operation in wider areas impossible.

Both multirotor and fixed-wing drones have their own advantages and disadvantages, and the multirotor is more versatile except that the fixed-wing has certain benefits when turning. Safety elements like "lost link and return-to-home failsafe" and geofencing which are built-in drones to elevate safety security during operation are commonly seen in drones. These steps may nonetheless not be sufficient enough to prevent cybersecurity, and this exemplifies the challenges faced in the dynamically changing digital era.

LiDAR provides a very good spatial map of wide airfields and is also able to detect objects from 0.5 cm to 10 mm. This family of features carries the promise of being applied in Foreign Object Debris (FOD) identification, which poses a great hazard to aircraft operation. The process of incorporating unmanned aerial vehicles is bothered by a variety of factors including different legislatures, communication problems between the drones and air traffic controllers, and the necessity to provide reliable cybersecurity security for the drone software.

Furthermore, the possibility of using unmanned ground vehicles (UGVs), which is also one of the technologies that are exploited to enhance efficiency and safety, will offer another layer of technological integration in airports.

UGVs work in conditions such as within confined spaces while moving luggage, towing aircraft, or doing inspections of areas like runways and taxiways. This type of drone may be capable of operating autonomously or remotely, which will eliminate the need for human presence in areas exposed to danger like those of the active runways. Through the automation of these simple yet critical tasks, UGVs will be able to reduce the chance of accidents while enhancing efficiency during ground operations. Moreover, their use could lead to a more uniform approach to time and tasks slated for performance, which in turn, can help in ensuring the constant improvement and the safety of the airports. Integration of UGVs with an aerial drone system means that a full intelligence and maintenance network is possible, taking the most advantage of cutting-edge technologies and thus ensuring a safer and more productive air space.

Finally, communication methods between flyers and ground workers are another important factor on which it has to work, that mainly through the use of radios and cellular phones, directs to the area for improvement. Drone technology has propagable potential for air traffic control activities by availing direct and smart communication with air traffic controllers, making both system and airport operations more efficient and safe.

Interaction with Industry Experts

Chris Baker, Ramp Agent, Pittsburgh International Airport

Chris Baker, a ground worker at Pittsburgh International Airport, discussed the inherent dangers associated with his role, emphasizing the risk factors, particularly within the ingestion zone around aircraft engines. He highlighted the inadequacies in safety training and the frequent accidents involving ground vehicles and workers. Chris pointed out the feasibility of drones for Foreign Object Debris (FOD) detection on runways, which he sees as a significant enhancement to safety and efficiency. He also suggested the potential use of sensors on planes or workers to maintain safe distances, thereby mitigating risks during ground operations.

Kendall King, Pilot, JetBlue

Kendall King, a pilot for JetBlue, addressed several issues faced by pilots at airports, including congestion, gate space limitations, and the inefficiencies of boarding and deplaning. While he has not encountered drone technology actively used at airports, he recognized their potential in FOD detection and perimeter security. Kendall noted the challenges in using drones for assistance during foggy landings, suggesting that while current technology like auto-landing systems and improved lighting could suffice, drones could play a role in enhancing runway safety but not directly in navigation during poor visibility conditions.

Gary Mitchell, Chief of Engineering and Construction, American Concrete Pavement Association

Gary Mitchell discussed the operational aspects and potential innovations at the airport, particularly focusing on the integration of drone technology. He elaborated on the daily checks for Foreign Object Debris (FOD) and the use of the Pavement Condition Index (PCI) to assess runway conditions. Gary is exploring the use of drones for better pavement management and efficient data collection, although challenges remain in ensuring drone safety and data accuracy. His insights also covered the difficulties in mitigating risks posed by unauthorized drones and the limited innovations in bird mitigation strategies, underscoring the complexities of managing airport environments.

Problem-Solving Approach

Problem Definition and Point of View Statement

After reviewing the information from our research and the insight that we gained from our interviews, we were able to narrow our focus to the current issues in FOD detection and removal. It became clear that not only was the amount of damage caused by FOD alarming, but the technology being used to handle it was not advanced or effective enough. Some of our key takeaways were: Advanced FOD detection systems are only being used in a handful of airports across the country. FOD was often both detected and removed by sending humans out on to the runway, posing a safety risk and liability. Removing FOD took an unnecessary amount of time and could lead to costly flight delays.

To reflect the current problems with FOD detection and removal we drafted a point of view (POV) statement to show how the issue effected one worker on a smaller scale. Our POV statement is as follows:

We met Derrick, a maintenance worker at Chicago International Airport. Derrick is in charge of driving his truck around the runways twice a day to look for and remove any FOD. It would be game-changing if new protocols or products could be put in place to make Derrick's job safer and more efficient.

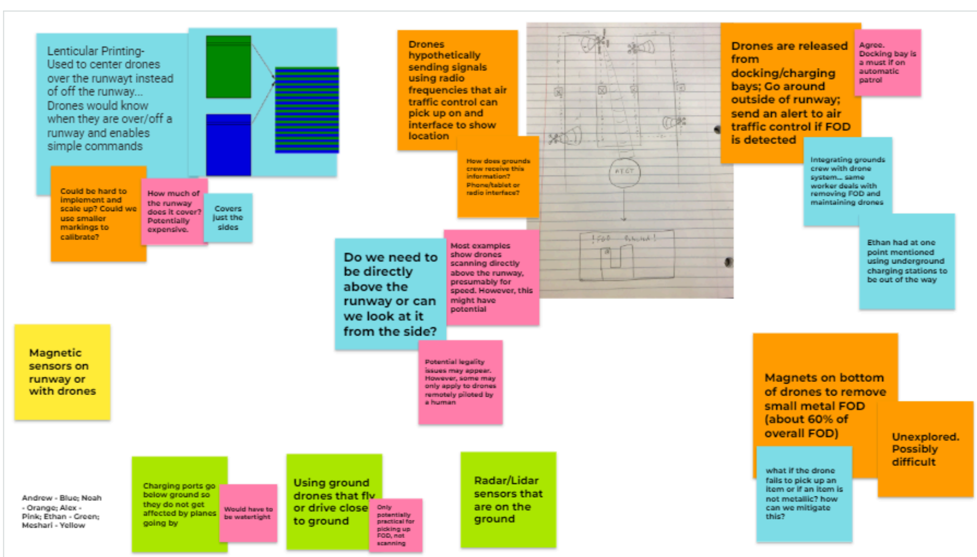
Brainstorming Approach

The brainstorming portion of our ideation process was defined in three parts: the individual brainstorming phase, group brainstorming phase, and iteration brainstorming phase.

This allowed each group member to effectively communicate their ideas and concerns regarding ideation.

The individual brainstorming phase utilized an allotted time frame of four days prior to our weekly meeting. Each group member investigated two ideas, one related to products, and one related to systems. Members were encouraged to deliver drawings or other proof-of-concepts to demonstrate their ideas. Each idea was proposed during our weekly team meeting where feedback and our first wave of iteration was administered.

The group brainstorming phase took place during the aforementioned weekly team meeting. Each member of the group was encouraged to share feedback and ideas based on the results of the individual brainstorming sessions. We utilized a "sticky-note" style technique to combine ideas and feedback into an organized document. In this document, we utilized color to distinguish between each group member. This concept board is depicted below in Figure 1.



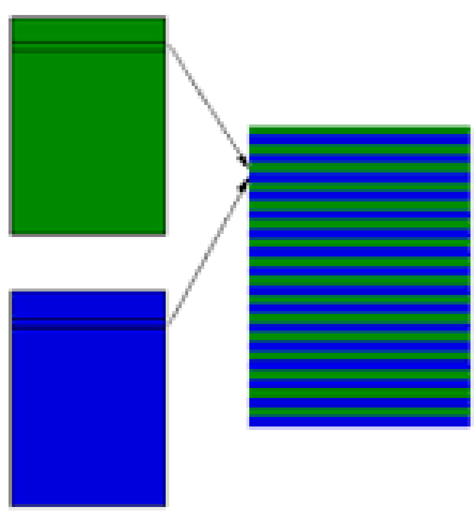
[Figure 1: Concept Board]

This concept board gave us a pretty good idea of the direction we would be taking for our prototyping phase, as demonstrated by the bunched up clumps of ideas and feedback. Our key ideas were delivered to industry professionals to receive new feedback and affirmation on the legitimacy of these ideas. After receiving feedback from these professionals, we moved into our last brainstorming phase, the iteration phase.

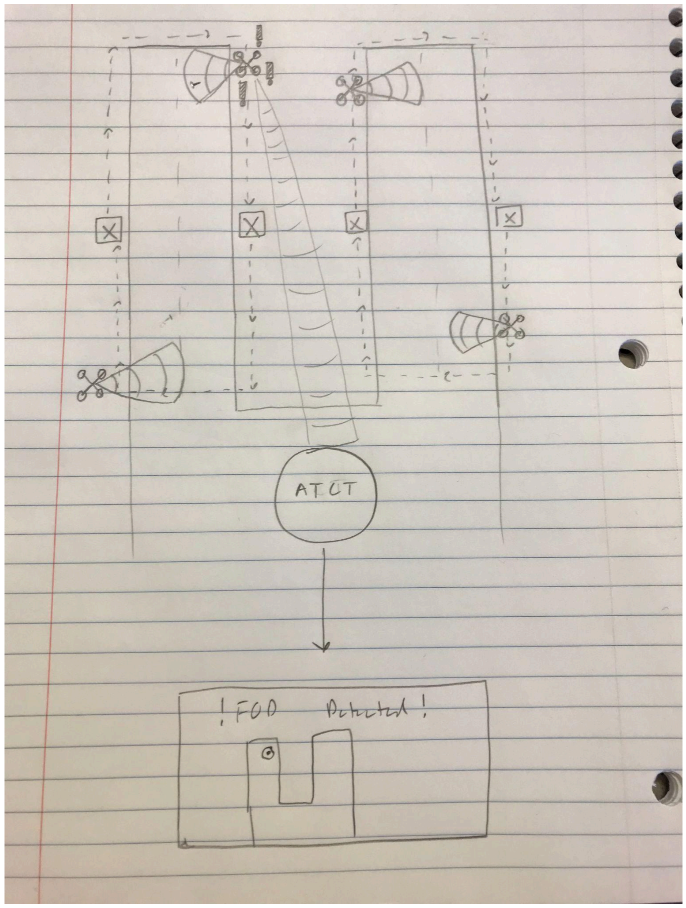
The iterative process utilized our best ideas from the previous phases, alongside feedback from industry experts, to further develop our ideas before prototyping. We decided to combine several ideas into two main proposals in line with our initial design philosophy: one system, and one product.

The iterated system shown below in Figure 2 utilized lenticular printings to guide air drones onto and off of the runway in order to scan for and remove FOD. The design would utilize pre existing air drone and sensor technology to drastically reduce risk and maintenance cost for airports.

The iterated product shown below in Figure 3 combined industry standard sensors, communication networks, and air drones to detect and remove FOD in a "surveying" fashion.



[Figure 2: Lenticular Printing Diagram]



[Figure 3: Drone FOD Detection System]

Technical Aspects of Design Development

Decision Matrix

The brainstorming activities allowed the team to develop four distinct ideas for solutions that would address the task of Foreign Object Debris detection. Each solution possessed unique attributes contributing to the viability for this project. To analyze these and find the best solution, the team made use of a decision matrix. The team came up with values that were important to the feasibility and usefulness of the product with a heavy emphasis on stakeholder feedback. Safety was given a weight of four out of five but split up into workers safety and plane safety giving each a weight of two. The complete decision matrix can be referenced in Figure 4.

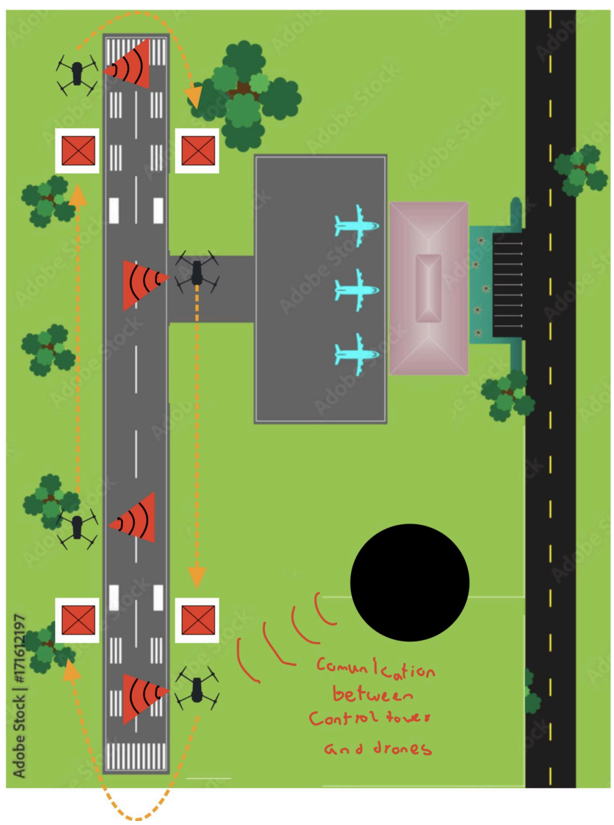
	Weight	Air Drone (Detection Only)	Air Drone (Magnet)	Ground Drone	Runway Sensors	
Stakeholder Feedback	5	1	2	4	3	
Cost Efficiency	1	2	2	2	4	
Complexity	3	2	1	3	3	
Efficiency (Speed)	5	2	3	3	1	
Upkeep	2	2	2	1	4	
Safety (Workers)	2	1	3	4	2	
Safety (Planes)	2	2	1	3	4	
Total Scores		33	42	62	53	
Notes		Dangerous for the planes, would need to look into all the rules and regulations regarding any flying of drones around airports	Seems hard to get it to pick anything up and very limited on what it actually would pick up	Great feeback from stakeholders, like that it can retrieve FOD just need to fully figure out the system that we would need to put in place to integrate this into airports now	Too easy, feels like we are playing it safe, similar things have been done already before	

[Figure 4: Evaluation of Solutions Through the Decision Matrix]

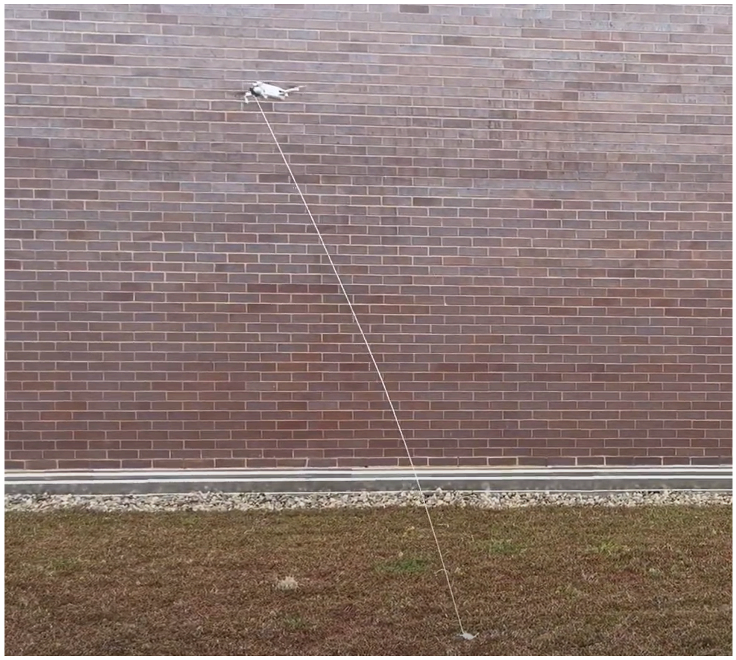
This step left the team with two options that were clearly better than the other two which was surprising since most of the research up until then was based on air drones. The team chose to combine ground drones and runway sensors to work together to find and collect FOD and also prototype the air drone with a magnet to leave no stone left unturned.

Rapid Prototyping

In order to help industry experts understand each solution during the team's interviews, they made rapid visual prototypes of each by drawing out a system for both of the ideas. The team also attached a magnet to a drone to see how difficult it would be to pick up screws and other small, metallic pieces on the runway. These simple prototypes also allowed the team to fully think through each iteration of the ideas to make sure it was feasible. Please reference Figure 5 through Figure 7 as well as their descriptions to see each of the prototypes. Once the team makes a final decision on the solution to continue developing, the team will further refine that prototype and turn it into a physical device.

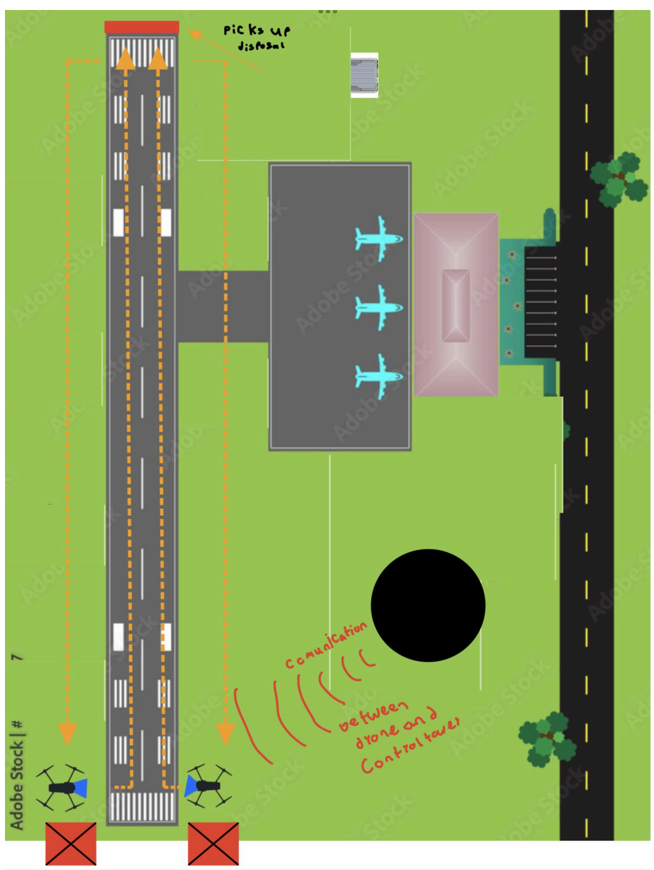


[Figure 5: Prototype 1 Visualization of Air Drone System]



[Link to the video of the drone picking up items using the magnet]

[Figure 6: Prototype 1 Testing Feasibility of using a Magnet for FOD Retrieval]



[Figure 7: Prototype 2 Visualization of Ground Drone System]

Stakeholder Feedback

We conducted an interview with Adam Brodin, Airport Operations Supervisor at Wichita Dwight D. Eisenhower National Airport, to share our ideas with someone who has experience in the drone/airport industry.The initial and most critical feedback we received pertained to FAA regulations, which pose certain limitations on our concepts. We realized the necessity to navigate around these regulations to advance our prototype. For instance, a specific regulation requires drones to maintain a distance of 250 feet from the landing strip, which complicates our proposal of deploying drones near the runway. Additionally, our original concept of placing charging docks around the landing strip had to be revised due to regulations prohibiting structures that could pose hazards in emergencies. This led to the innovative idea of developing underground or concealed charging docks that comply with these guidelines.

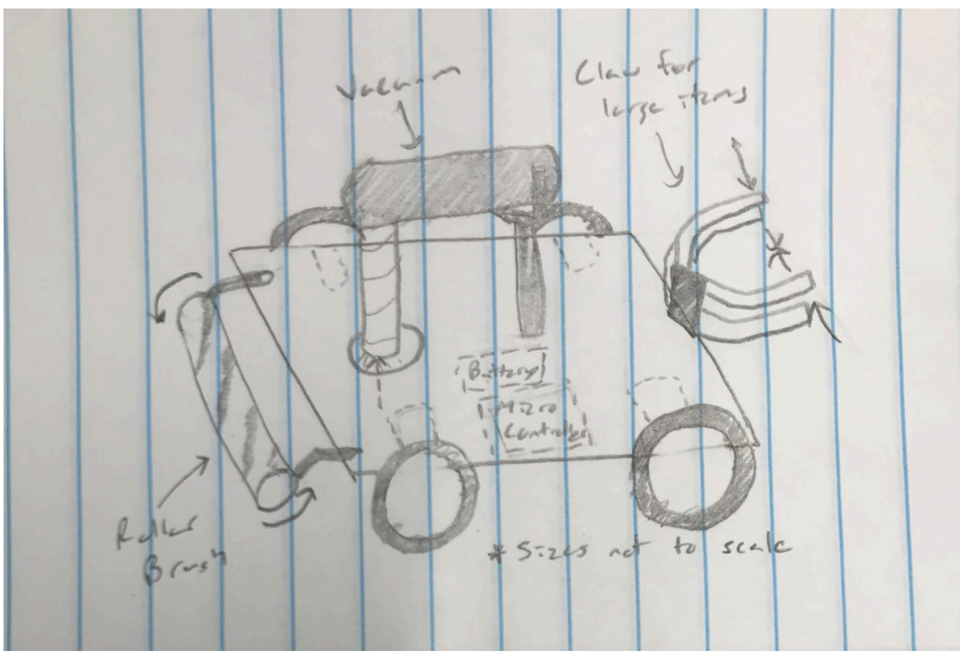
Further feedback highlighted that using drones for Foreign Object Debris (FOD) detection from an aerial perspective is already a common practice, advising us to either diverge from this approach or enhance the accuracy of the FOD detection devices. Consequently, we pivoted towards drones capable of not just detecting but also retrieving objects.

General feedback on several of our ideas was positive, yet it emphasized the critical need for careful implementation. This focus stems from the extensive regulations and prevailing skepticism regarding drone usage. Effective implementation is crucial for our ideas to benefit airports universally.

Adam suggested that equipping drones with magnetic sensors or brushes to remove or collect FOD could represent a significant innovation in the field. Such a feature would be a market breakthrough and facilitate the acceptance and adoption of our ideas across airports if the prototype and implementation phases are executed successfully, indicating a substantial market opportunity.

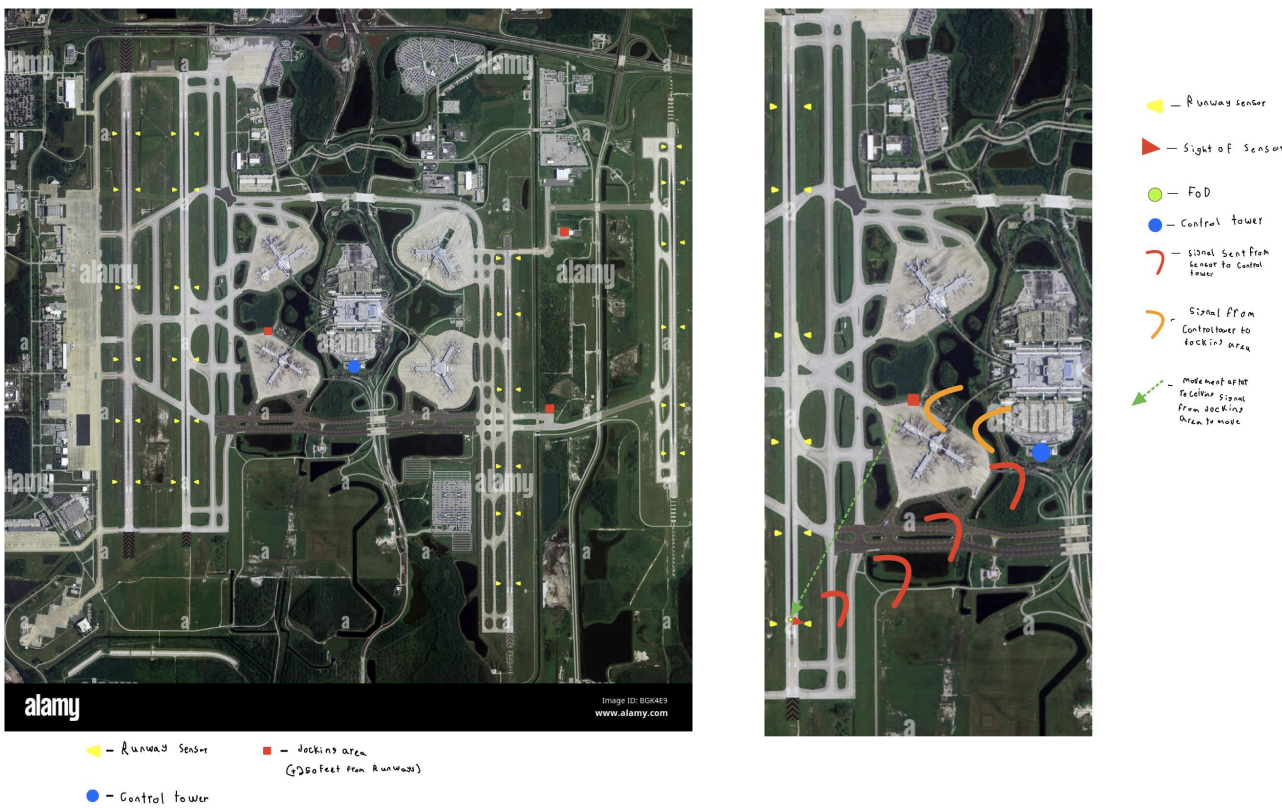
Final Prototype

With both the decision matrix and industry experts supporting solution two, the team decided to focus the project on this design and continue refining the system and the prototype. The team sketched out a preliminary idea of attachments needed to collect the widest array of different types of FOD, that sketch can be found below in Figure 8. The sketch was used to see what materials were needed. An empty chassis with motors, a claw with servo, vacuum, and roller was purchased.The team had an arduino to use to control the vehicle. The team designed and 3D printed parts to attach everything to the chassis and keep functional.

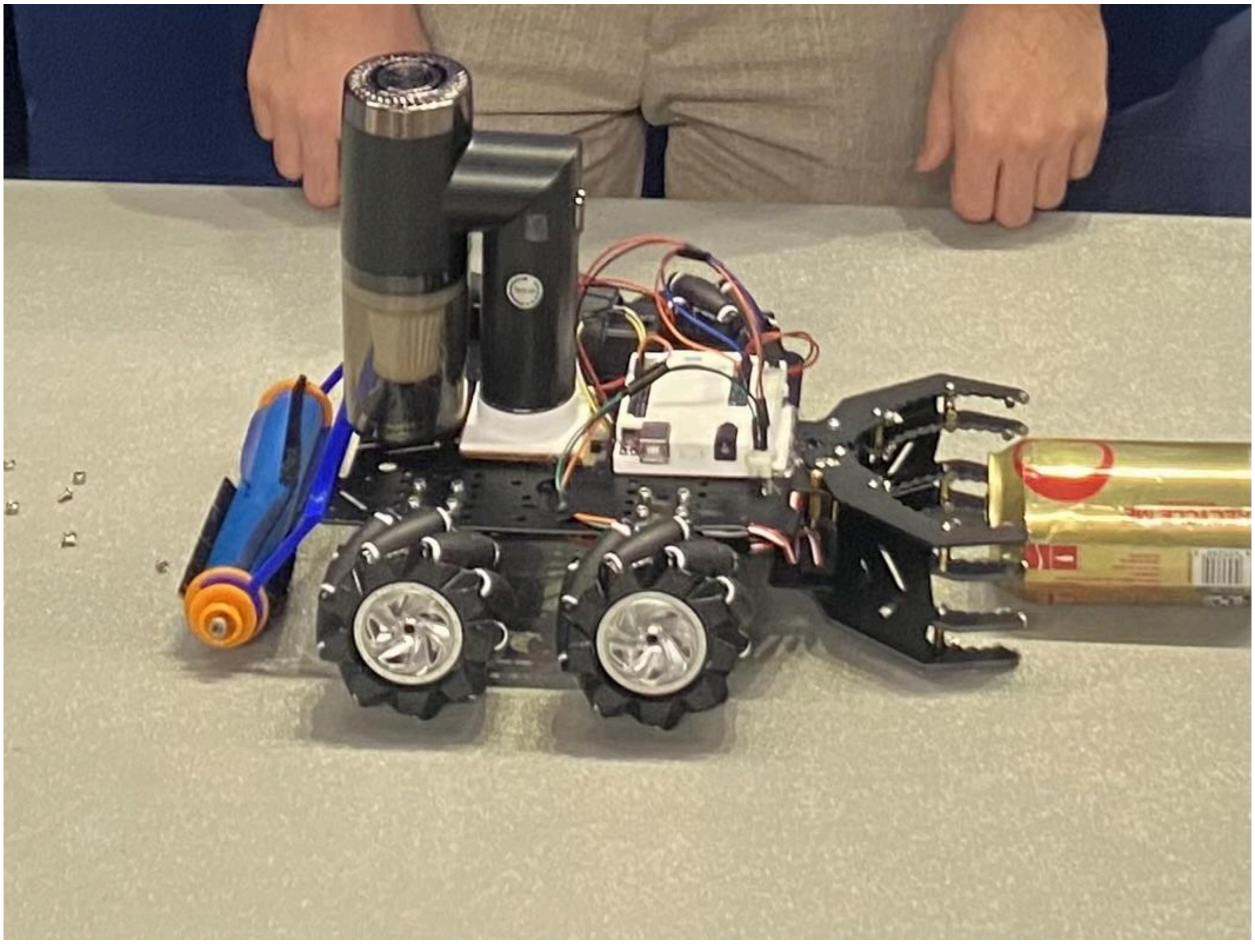


[Figure 8: Outline for Final Prototype]

While part of the team was building the vehicle, the other part of the team was working on how to integrate this system into the Orlando International Airport to get a better idea of the costs for a full size integration plan. The sketch of how the system works and what it looks like in the full airport is found in Figure 9. The sensors on the runway are based off of a system that is already being used in select airports created by Xsight Systems. When the sensors find an abnormality it uses image recognition to determine how large the object is and pinpoints exactly where the object is. A signal would be subsequently sent to the air traffic control tower where they would make sure that the runway is safe. In which case, the go ahead would be given to our unmanned ground vehicle (UGV) and it would retrieve the object autonomously, using the sensors as its eyes.



[Figure 9: Overview of the Airport with the System and Example of a Use Case]



[Figure 10: Final Prototype]

As seen above in Figure 10 the vehicle has a multitude of different addons for different types of FOD. On the left side of the picture there is a roller and vacuum for smaller objects like screws, nuts, and bolts. On the right side of the picture is a claw for larger objects like sheet metal or large rubber from popped tires. As a third failsafe, there are small magnets throughout the claw to help with grip and pick up a large amount missed by the roller and vacuum. Depending on the signal given by the sensors on how large or small the object is, is how the vehicle will orientate itself. Then it would return back to its charging bay where the objects would be collected. The team put a heavy emphasis on designing a prototype that would work.

Future Modifications/Improvements:

This initial prototype serves as a scaled-down proof-of-concept, primarily to show how it would integrate into a real airport and to allow people to visualize exactly what our autonomous vehicle would look like scaled down. However, this prototype could still be improved in the final design. Firstly, the roller in the front of the vehicle should be motorized and split into two and angled so that it would collect any FOD and spit it inwards towards the mouth of the vacuum which would allow for a greater area of effect to pick up the FOD. Another modification would be taking away the omnidirectional tires and adding normal ones that turn like any other car. The omnidirectional tires were not as useful as we thought, and the regular ones would work better with the roller and vacuum section. Additionally, our final design would include a higher powered vacuum that is custom built to the shape of the vehicle rather than the current one that protrudes up.

Risk Analysis

We identified a few key risks associated with our solution. Those key risks include, but are not limited to, water damage, software and hardware malfunction, the UGV getting caught on large FOD, malfunctions related to the home docking station, communication failure with traffic control and slow response from a grounds crew operator.

The key risks of our project along with their expected frequency, severity, and mitigation strategies are displayed below (Figure 11).

Likelihood/Severity	Minimal	Minor	Major	Hazardous	Catastrophic
Frequent					
Probable					
Remote		4 - Dock Error	2 - Stuck on FOD; 6 - Slow Operator		
Extremely Remote			1 - Water Damage; 3 - Software Error	5 - Comms Error	
Extremely Improbable					

	RISKS	MITIGATIONS
1	UGV shorts due to water damage	Waterproof covering, Waterproof case for internal electronics, Procedure doesn't permit use during heavy rain
2	UGV is caught on large FOD	Claw tool used to dislogde large FOD, Sensor picks up on FOD size and procedure permits maximum FOD size for autonomous removal
3	UGV malfunctions due to software issue	Rigorous testing and periodic calibration and testing. Program in failsafes that return UGV to charging port (manual/autonomous return to home protocol)
4	UGV has charging/docking malfunction	Routine Maintainance Check. UGV sends an alert to operators when it cannot dock or is low on battery, operators are trained to take appropriate action
5	Communication malfunction with air traffic control or ground maintenance	Return to home protocol upon signal loss
6	On-call Grounds crew operator takes too long	Periodic rigourous training protocols.

[Figure 11: Risk Analysis Chart]

After thorough consideration by our team, we have deemed all of the risks acceptable if given the implementation of their respective mitigations. The most crucial risks to look out for are the ones that could prevent the UGV from leaving the runway. If the UGV fails to leave the runway it would become as equally hazardous as a large piece of FOD, that is to say, no air vehicles can safely operate while it is still on the runway. Risk that would cause this are technical malfunctions and the UGV getting stuck on FOD, which would prevent the UGV from successfully executing its emergency return-to-home protocol that would execute if it were to lose signal or some unforeseen event happens that contradicts the information or data sent to it. In the event that the UGV cannot leave the runway, trained operator(s) will be sent to retrieve the vehicle quickly, before it can become a hazard. It is for this reason that the slow response of an operator is classified as a higher threat than technical malfunctions.

Projected Impacts of the Team's Design and Findings

Cost Benefit Analysis

This section covers the costs and benefits associated with our proposed solution. The total cost of the project is covered in Tables A, B, and D. The benefit that this solution would provide for a singular standard airport is given in Table C. A 5-year Cost vs. Benefit Analysis (CBA) is provided in Table E to show the payback and annual return on investment of the proposed solution. Overall, we found our solution to have a payback period of 3.8 years, and a Benefit-Cost Ratio of 1.25 after 5 years (see Table E).

The initial costs of the system are laid out in Table A. Before an unmanned ground vehicle (UGV) is manufactured it must first be researched and developed (R&D). We estimated this R&D cost of $1.5M by scaling up the R&D cost of a home cleaning robot[2]. Next, we estimated the cost to install all of the hardware installation, mainly charging/docking bays, to be $10,000 for an airport. For a standard airport with 2 of our vehicles, the cost to manufacture the UGVs would be $80,000[3]. Finally, if we are implementing an already on the market FOD radar detection system for a 4 runway airport it would cost around $5M[4]. This brings the initial production and installation costs to around $6.5M for a standard airport.

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[2] Sheykin, H. (2023, November 10). *How Much Does It Cost to Launch Autonomous Home Cleaning Robots?*. FinModelsLab. https://finmodelslab.com/blogs/startup-costs/autonomous-home-cleaning-robots-startup-costs
[3] *C37 AMR Robotic Floor Scrubber Sweeper*. (n.d.). Crystal Floor Scrubber. https://www.crystalfloorscrubber.com/product-page/c37-amr-robotic-floor-scrubber-sweeper?srsltid=AfmBOorhBkzlb_cmLxPEWf0rpP8aHA8Bf9AWlxbe-0yRVKNauzTu77DFx9I
[4] *Sea-Tac Airport Becomes Second in U.S. to Install Runway Debris Safety Detectors.* (2015, November 23). Port of Seattle. https://www.portseattle.org/news/sea-tac-airport-becomes-second-us-install-runway-debris-safety-detectors

A. Production and Installation Cost				
Item	Rate	Quantity	Subtotal	Remarks
Labor				
Research and Development	-	-	$1,500,000.00	based on 2x of R&D costs for home cleaning robots
Hardware Installation	$1.00	10,000	$10,000.00	Installing charging ports and infastructure needed like sensors on the runway
Expenses				
UGV materials cost	$40,000	2	$80,000	$40,000 per, 2 UGVs
FOD detection hardware/sys	$1,250,000	4	$5,000,000	$1250000 per runways, 4 runways
Total			**$6,590,000**	

[Table A: Production and Installation Costs]

After the system has been implemented, it will have necessary ongoing costs, as shown in Table B, to keep it running and maintained. Using an industry average of $1,420 to train an employee every 3 years[5], we can estimate that the annual cost to train 7 operators and crew would be almost $10,000. Additionally, if the airport requires a UGV operator to be on-site 24/7 (assuming 3 workers, covering 8 hours shifts), their combined yearly salary would come to about $300,000[6]. Electricity can be estimated to about $1 a day for each UGV[7]. Finally, we can estimate the maintenance costs by using an annual estimate of 20% of the vehicle's production cost[8]. This brings the annual cost to operate and maintain our system to about $330,000.

[5] *Training Expenditure per Learner in the Training Industry in the United States from 2015 to 2023, by Company Size*. (n.d.). Statista. https://www.statista.com/statistics/795795/training-expenditure-per-learner-and-company-size-us/#:~:text=In%202023%2C%20small%20companies%2C%20with,decrease%20from%20the%20previous%20year

[6] *Airport Ground Staff Salary.* (n.d.). ZipRecruiter. https://www.ziprecruiter.com/Salaries/Airport-Ground-Staff-Salary

[7] Voelcker, J. (2023, September 17). *How Much Does It Cost to Charge an Electric Vehicle?*. Car and Driver. https://www.caranddriver.com/news/a45036169/electric-vehicle-ev-cost-to-charge/

[8] *The ROI Of Autonomous Mobile Robots In Your DC.* (2020, February 3). Lucas. https://www.lucasware.com/the-roi-of-autonomous-mobile-robots-in-your-dc/#:~:text=Based%20on%20published%20reports%2C%20the%20cost%20per,approximately%20$30%2C000%2C%20plus%2020%20percent%20annual%20maintenance

B. Ongoing Cost				
Item	Rate	Quantity	Subtotal(per year)	Remarks
Labor				
Training the Staff	$473.33	21	$9,940	Based on cost of $1420 to train an employee every three years
Operator Wage	$102,200	3	$306,600	yearly wage of $102,200 with three operators working three shifts
Expenses				
Electricity	$365	2	$730	$365 per year, 2 UGVs
Maintenance	$8,000	2	$16,000	20% of production cost annually
Total			**$333,269.93**	

[Table B: Ongoing Costs]

While these might seem like large upfront and annual investments, as shown in Table C, the benefits our system offers are tremendous. A 2023 FAA report[9], found that the standard airport (440,000 operations per year) experiences an average of $1,042,475 in direct FOD costs. These direct costs include damages to airplanes and the cost associated with repairing them. If our system works effectively, it can eliminate nearly all of the direct FOD costs that an airport experiences. In addition to direct costs, FOD causes indirect costs, namely in the form of delayed flights due to FOD on the runway. While these costs are difficult to calculate, the FAA uses a "modest" 1x multiplier on the direct costs to find the indirect costs (some estimates suggest that the multiplier can be as much as 8x to 12x). We used the same 1x multiplier in our CBA, this gives us a total annual benefit of just over $2M.

C. Benefits				
Item	Rate	Quantity	Subtotal	Remarks
Tangible				
Direct FOD Cost Reduced	$2.37	440,000	$1,042,475.75	Standard large airport has about 440,000 operations per year
Intangible				
Indirect FOD Cost (see list below) Reduced	-	-	$1,042,475.75	Using "modest" Direct Costs 1x multiplier from FAA report
Total			**$2,084,951.50**	

[Table C: Benefits]

[9] *Foreign Object Debris Detection System Cost-Benefit Analysis*. (2023, May). Federal Aviation Administration. https://www.tc.faa.gov/its/worldpac/techrpt/tc22-47.pdf

To look at the longer term benefits of our system, we first calculated the costs of our solution over 5 years as shown in Table D. If we sum the upfront production and installation costs with 5 years of ongoing costs we get a 5 year cost of about $8.25M.

D. 5 Year Summary of Cost				
Item	Rate	Quantity	Subtotal	Remarks
Net Values				
Production & Installation	$6,590,000	1	$6,590,000	From Table A
Ongoing Cost	$333,269.93	5	$1,666,349.65	From Table B
Total Cost			**$8,256,350**	5 Year Cost

[Table D: 5 Year Summary of Cost]

Finally, we can combine all of these figures to find the benefit versus the cost as shown in Table E. Our solution has a payback period of 3.8 years. This is quite a quick return on investment considering the large upfront cost. After 5 years, our solution provides a benefit to cost ratio of 1.26. This means, once the payback period is exceeded our system has the potential to save an airport almost $2M each year.

E. Benefit v. Cost Analysis (5 Years)				
Item	Rate	Quantity	Subtotal	Remarks
Net Values				
Total Cost	$8,256,350	1	$8,256,350	Initial Cost + 5 Years of Ongoing Cost from Table D
Total Benefit	$2,084,951.50	5	$10,424,757.50	5 Years of Annual Benefit
Analysis				
Benefit to Cost Ratio (Total Benfit/Total Cost)			1.26	Benefit Outweighs Cost
Payback Time (years)			**3.8**	Initial Investment/(Annual Benefit - Annual Cost)

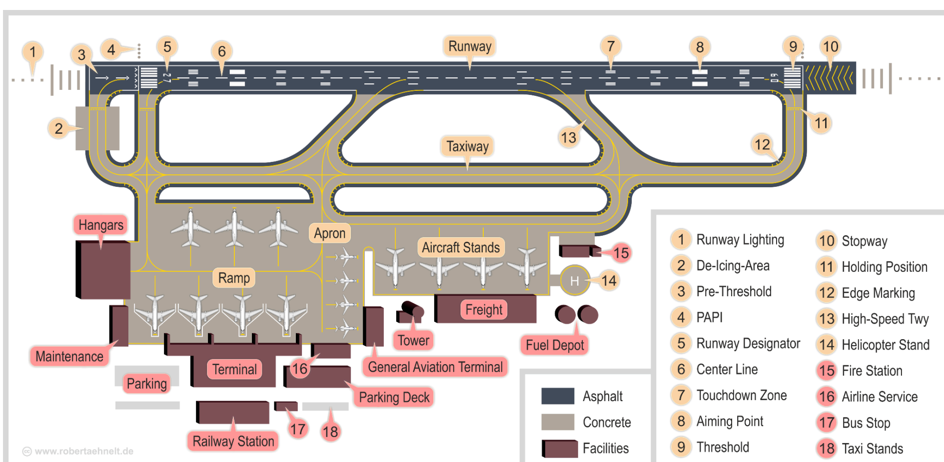
[Table E: 5 Year Benefit vs. Cost Analysis]

Future Implications

Based on the relatively quick payback period and tremendous annual savings, it is clear that our design is financially and commercially viable for airports of all sizes. However, the team's vision is to create a system that is constantly advancing and evolving. Over the next few years our system would add capabilities for the unmanned ground vehicle (UGV) to go on taxiways and all tarmac areas, add a mobile app for ground workers, and add our own FOD detection system. These functionalities are not part of our current design, but could lead to even greater safety and cost benefits for airports.

Expanding UGV Range

Our current UGV is only designed to drive on and remove FOD from the runways. While its charging/docking bay is situated on/near the taxiway or apron to comply with FAA standards, it is not designed to remove FOD from the taxiway, apron, or ramp areas. Although planes are



[Figure 11: Diagram of an Airport Tarmac; Source: wikipedia.org/wiki/Airport]

not landing or taking off in these areas, FOD still poses a major problem. Planes still must run their engines to propel themselves around the tarmac and they also risk damaging their tires in these areas. FOD walks are a regular procedure done by ramp agents in the ramp area, but FOD is less regularly patrolled in the apron and taxiway areas. In the future our system could be modified to remove FOD from these areas as well. However, this would require greater innovation since these areas have higher traffic and would not have their own detection system like the runways do. But with advanced sensor systems on the UGV, the vehicle could be updated to patrol the areas on its own while navigating the denser traffic.

App for Grounds Crew

Our system is currently designed to interface with a display in the air traffic control tower where the UGV operator/manager would sit. However, this means communication with the maintenance and grounds crew workers on the tarmac is only being done with voice communications. Our system could be modified to have a mobile app interface for ground operator's phones or tablets. This could visually show them where the FOD is being detected and the status of its removal. It could send alerts with tagged locations to notify workers if they need to assist in removing a piece of FOD that the vehicle is unable to remove or if the vehicle needs to be moved off of the runway. This would help improve communication across all workers and operators that interact with the UGV.

In-house FOD Detection System

Currently, FOD detection systems are only used in a handful of airports. This gives them a steep price tag (about $5M for a standard airport) and makes them have slower installation times. If our system were to come with its own FOD detection system it could greatly reduce the upfront cost and yield a quicker payback period to the airport. Additionally, it would eliminate any hurdles with integrating the UGV and detection system communications. There are a variety of technologies being used from radar to lidar to image recognition, our design would incorporate the technology that has proven itself most effective in the next few years.

Appendix A: Contact Information

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Appendix B: University Description

Penn State University is an institution of higher education in Pennsylvania. It houses the college of engineering which includes numerous engineering degrees at both the undergraduate and graduate levels. The college of engineering supports an undergraduate minor in engineering leadership in which undergraduate engineers can build the non-technical skills to support the great technical skills they are developing through their engineering curriculum. The engineering leadership development program offers students classes in project management, leadership education and development, business basics, and cross cultural teaming. Students in the minor are dedicated to building these skills in addition to the technical work load required of their discipline's curriculum. The engineering leadership program also offers a graduate program in the form of a master of engineering and an online graduate certificate in Engineering Leadership and Innovation Management.

Appendix C: Industry Experts

Mr. Gary Mitchell

- Vice President, Chief of Engineering and Construction, American Concrete Pavement Association

Adam Brodin

- Airport Operations Supervisor, Wichita Dwight D. Eisenhower National Airport

Chris Baker

- Ramp Agent, Pittsburgh International Airport

Kendall King

- Pilot, JetBlue

Appendix E: Educational Experience and Evaluation Questions

1. Did the Airport Cooperative Research Program (ACRP) University Design Competition for Addressing Airports Needs provide a meaningful learning experience for you? Why or why not?

Yes, the competition provided real-world engineering and business experience for the team and simulated teamwork in a professional setting.

2. What challenges did you and/or your team encounter in undertaking the competition? How did you overcome them?

One challenge our team faced was defining the scope of our problem and solution. We initially started on a completely different challenge topic and we were creating solutions that did not match our problem statement. We eventually switched our problem to FOD detection and additionally towards the end of the project we changed from focusing on air drones to focusing on ground vehicles. We also were initially unable to secure interviews with experts directly related to our problem, but eventually after being in communication with them for several weeks we were able to secure an interview with a very relevant stakeholder.

3. Describe the process you or your team used for developing your hypothesis.

We started by compiling our own ideas of what the biggest problems at airports are. Then we met with a few industry professionals and experts and compared those ideas. We received positive feedback on some ideas and negative feedback on others. Once we settled in to focusing on FOD detection we ran some of our initial prototype ideas by another stakeholder which allowed us to finally narrow our scope to ground vehicles for FOD detection.

4. Was participation by industry in the project appropriate, meaningful and useful? Why or why not?

Yes, while we didn't necessarily have an interview with someone who dealt directly with FOD, we had several interviews with airport professionals. These interviews gave us a greater understanding of the airport landscape and also gave us someone with the appropriate knowledge to run our ideas by.

5. What did you learn? Did this project help you with skills and knowledge you need to be successful for entry in the workforce or to pursue further study? Why or why not?

We learned that it is never too late to change your idea. We were able to adapt as new information came in rather than staying rigid to our original ideas. This project helped each of us learn how to lead a team and use resources outside of the team well. It gave us exposure to how an engineering project could be researched and managed. Additionally, this project allowed us to learn some of the business side of things like how to develop a cost-benefit analysis. Overall, this project provided both technical and soft skills that each of us can take into our future schooling and careers.

Appendix F: References

(literature review and footnoted references)

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