ACRP CHALLENGE: AIRPORT OPERATIONS AND MAINTENACE

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RunwAI

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ENGINEERING DESIGN AND INNOVATION

Executive Summary

In this proposal, a team of five multidisciplinary undergraduate students at The Pennsylvania State University's Engineering Leadership Development program proposes a solution to automate current friction testing equipment of runways at large scale airports. The proposal targets the ACRP Design Challenge- Airport Operation and Maintenance: *Exploring new methods for design and maintenance of pavement surfaces and markings*. The team proposes an electrical, automatic solution that increases efficiency of friction testing through image subtraction and artificial intelligence, hence the name RunwAI. The team has thoroughly analyzed the potential industry impact of RunwAI through cost-to-benefit analysis, a formal risk assessment, and conducting interviews with experts in the field. After a thorough analysis, the team concluded that the proposal was feasible, innovative, and will make a great contribution to airports. For an industry that is moving towards automation, RunwAI is the first step to future automation systems. By using this device, airports can save money on reduced vehicle driver hours, less vehicle damage, and mitigate any injuries for operators, all while further improving the accuracy of their friction testing equipment. In addition to the tangible benefits, RunwAI improves the efficiency of rubber detection, testing, and removing processes.

Table of Contents

Problem Statement and Background Information

This project's design challenge is proposed as a solution for challenge section A: "Exploring new methods for design and maintenance of pavement surfaces and markings", from the design category "Airport Operation and Maintenance" (Airport Cooperative Research Program (ACRP) University Design Competition for Addressing Airport Needs, 2022, p. 6).

As large commercial airport runways experience airplane landings at high volume, rubber from landing gear becomes deposited onto the underlying pavement. When sufficiently accumulated, the rubber can cause unsafe operating conditions for airports. Surface grooves cut into the runway to increase drainage and friction can become saturated with rubber. This results in a reduced coefficient of friction and an increased risk of hydroplaning in wet conditions. As a result, airports have needs to both measure and remove this rubber periodically.

According to the ACRP Synthesis 11, an average landing leaves as much as 1.4 pounds of a thin layer of rubber on the runway. The heat generated by the plane landing causes a chemical reaction that polymerizes the rubber, changing the rubber deposits into a hard, smooth material (ACRP Synthesis 11). This poses many issues for consistently safe takeoffs and landings for all aircraft on the tarmac. For example, polymerized rubber reduces the friction of the runways with the aircraft tires, which affects the breaking and controls of the aircraft (ACRP). When wet, it creates an extremely slippery surface to land on, which can cause hydroplaning of the aircraft. Therefore, maintenance of runway surfaces in a condition that allows for safe takeoff and landing for all aircraft is crucial.

According to the Airport Services Manual, the frequency of testing the friction of a runway depends on the number of flights taking place and the average weight of the aircraft. Figure 1, taken from Part 2, Chapter 8 of Airport Services Manual shows the minimum number of times that an airport operator(s) needs to close off a runway to perform a friction test, which on larger runways can take 7-8 hours.

Daily turbo-jet aeroplane arrivals for runway end	Annual aeroplane weight for runway end (million kg)	Minimum friction survey frequency
Less than 15	Less than 447	Once per year
16 to 30	448 to 838	Once every 6 months
31 to 90	839 to 2 404	Once every 3 months
91 to 150	2 405 to 3 969	Once every month
151 to 210	3 970 to 5 535	Once every 2 weeks
Greater than 210	Greater than 5 535	Once every week

[Figure 1: Frequency of Runway Visual Inspection Reports]

Current continuous friction-measuring devices all operate using the same principle. In a manual process, a smooth tread tire is towed behind a truck and calculates coefficients of friction using data collected by the device. According to Civic Aviation Authority, “The success of friction measurements depends heavily on the personnel responsible for operating the device. Adequate professional training in the operation and maintenance of the device and procedures for conducting friction measurements is essential to ensure reliable friction data… If this is not done, then personnel fail to maintain their experience level over time and lose touch with the new developments in calibration, maintenance and operating techniques” (Civic Aviation Authority).

The goal for this project is to design a solution that automates the friction testing already done by airports in order to provide the necessary step for future automation. This solution is designed to reduce the long-term maintenance costs associated with runway repair, minimizing the cost a runway will incur throughout its pavement life cycle, as well as improving the safety of takeoff and landing of all aircraft.

Summary of Research

Point of View Statement

Large general aviation airports with heavier loads and high-volume air traffic need an automated system to friction test rubber deposits to minimize runway slippage and reduce contaminants. This is important to allow for safe takeoffs and landings, minimizing long-term maintenance costs, and ensuring the longevity of runways.

Airport Literature Review

Federal Aviation Association - Guidelines and Procedures for Maintenance of Airport Pavements

This document goes into detail on the non-mandatory guidelines and procedures for maintaining airport pavements. The most useful parts of the document will come from Chapters 4 and 5. Chapter 4 talks about the importance of inspecting pavement and the record keeping involved. Chapter 5 talks about materials and equipment that are currently used to maintain runways. Overall, this document will mainly be used to justify and incorporate future AI applications mentioned in the “Future Impacts” section of the “Projected Impacts of the Team’s Design and Findings”. When the design is created, it will need to be determined how effective it must be to beat current friction measuring methods as well as how often the design will be used.

Airport Services Manual - Part 2: Pavement Surface Conditions

This manual details material on factors affecting friction and friction measuring devices on paved surfaces. It also mentions "practices for measuring and reporting friction values on snow, ice, and water covered surfaces" as well as "clearance and removal of contaminants and debris from the movement area" as detailed in the Foreword of the document. This document can be used as a basis for the current friction testing methods (Chapter 5, Runway friction measuring devices), removal of rubber (Chapter 8, Removal of rubber), and determining how often friction tests should occur (Appendix 2).

Interaction with Airport Operators and Industry Experts

To aid in research, the team contacted and interviewed three experts from the airline industry: David Lange, Ph.D., Professor at the University of Illinois, Department of Civil and Environmental Engineering; Kyle Potvin, Vice President at Applied Pavement Technology; and Gary Mitchell, Vice President at Airport and Pavement Technology American Concrete Pavement Association.

Dr. David Lange

The team's discussion with Dr. Lange helped narrow the scope of the design solution and he offered the team insight, resources, and direction for the project. Dr. David A. Lange is a retired professor at the University of Illinois in the Department of Civil and Environmental Engineering, specializing in airport pavement materials. He is now the Director of Excellence for Airport Technology. Dr. Lange discussed the Transportation Research Board's Annual Meeting and advised the team to go on their website and combine presented solutions and current research for the team's project. He encouraged the team to contact airport maintenance teams at the

Philadelphia and Pittsburgh International Airports to learn about current funding and critique it for the team's own project. Another great resource that Dr. Lange gave the team was the Federal Aviation Administration (FAA) William J. Hughes Technical Center in Atlantic City, which provides current aviation research topics. Located at the William J. Hughes Technical Center is the National Airport Pavement Test Facility which provides high quality test data from both rigid and technical pavements subjected to simulated airport traffic. Dr. Lange directed the team to research reflective cracking and recyclable pavement materials in their Airport Research and Development Technical branch.

Due to the diverse composition of technical backgrounds present within the team, Dr. David Lange advised the team to focus on airport runway maintenance and preservation over pavement materials and construction. One idea Dr. Lange provided was Rubber Removal Techniques on Runways by the National Academy of Sciences. He encouraged the team to look through brilliant ideas to inspire further design and next steps.

Mr. Kyle Potvin

The team's discussion with Mr. Potvin gave them a much better reference for the current state of issues with airport pavement as well as some of the changes that have occurred over the years and possible future solutions.

Mr. Potvin began by discussing the current state of the industry. He informed the team that many airports are part of the National Plan of Integrated Airport Systems (NPIAS), which provides annual federal funding for over 3,300 airports to use for maintenance, repair, and upgrade projects. However, the program has strict standards and to qualify, airports must show need for the grants, and they must also create a Pavement Maintenance Plan to ensure that they are ensuring the long-term support of the projects being funded, among other requirements. Most of the money airports spend comes from federal funding, with about 10% divided between local or state funding and the airport's revenue. He explained that it is crucial for airports to properly maintain their pavement surfaces, as a major rebuild of an airport the size of University Park Airport could cost upwards of $20 to $30 million, while maintenance and preservation are much less costly. Currently, pavement is generally rigorously evaluated about every 3 years, though airports make routine safety checks ranging from every few hours to once a day in an effort to avoid major stoppages and reconstruction projects.

One major question that Mr. Potvin answered for the team was about how airport pavement development and maintenance is affected by climate. Overall, the industry aims for approximately the same life and performance out of pavement across climates. However, he explained that based on the climate, different pavement designs are utilized to counteract climate-specific problems. In northern areas or others such as the southeast that experience large amount of precipitation, it is crucial to prevent moisture penetration, which has the chance to cause structural breakdowns, by sealing cracks and using designs that prevent moisture from getting into underlying layers. Specifically in the northern, colder climates, freeze-thaw cycles must be considered as they are a frequent cause of cracks. In the southern portions of the country, particularly the southwest, intense solar radiation can cause pavement to shrink as petroleum-based materials evaporate, causing cracking.

Mr. Potvin also explained what direction the airport pavement industry has been moving in. He said that it is possible that the FAA changes from supporting a 20-year designed life of pavement to a 40-year designed life, which would force much more rigorous maintenance and encourage innovation. He also mentioned that while there is a mass amount of highway-specification asphalt produced, it is much more expensive to produce small batches of airport-specification asphalt. There is a push to allow small airports that only service smaller jets to be able to make use of the highway-specification asphalt to reduce development costs. He also mentioned that new technology such as unmanned aircrafts, including drones, are being used to automate foreign object debris (FOD) removal, but the technology is still inferior to manual work.

The most urgent problems for the industry according to Mr. Potvin primarily relate to funding. He says that if small, local airports that service mostly corporate travel can receive more funding, it would be able to positively impact the environment, economy, and community. He also said that it is crucial for airports to prioritize maintenance with their funding, rather than saving it for larger projects as they have historically done, to save money in the long run.

Mr. Gary Mitchell

Interviewing field expert Gary Mitchell was very helpful in determining the scope and the direction in which the project will proceed. Not only has Mr. Mitchell worked in the industry for many years but he is also currently on the FAA Advisory research committee. Mr. Mitchell provided the team with resources and contacts to further the investigation of possible solutions and information on current research that is being conducted.

Throughout the interview Mr. Mitchell referenced current solutions to solve pavement cracking such as alkaline heavy cements, phase change materials, as well as geothermal energy sources for heating and cooling. While this information was very beneficial in the sense that it allowed the team to see current solutions to pavement cracking and imperfections, but it also brought up and furthered the idea of rubber removal for runways.

Rubber removal currently for runways is very important to ensure safe conditions for aircrafts and effective landings. Mr. Mitchell explained that this is a field that does not have standardized practices and requires a solution to better current standards. Rubber removal hiders a great cost on airports around the United States and is in need of an innovative solution to control runway damage and deterioration as well as water runoff from current methods.

Interdisciplinary Problem-Solving Approach

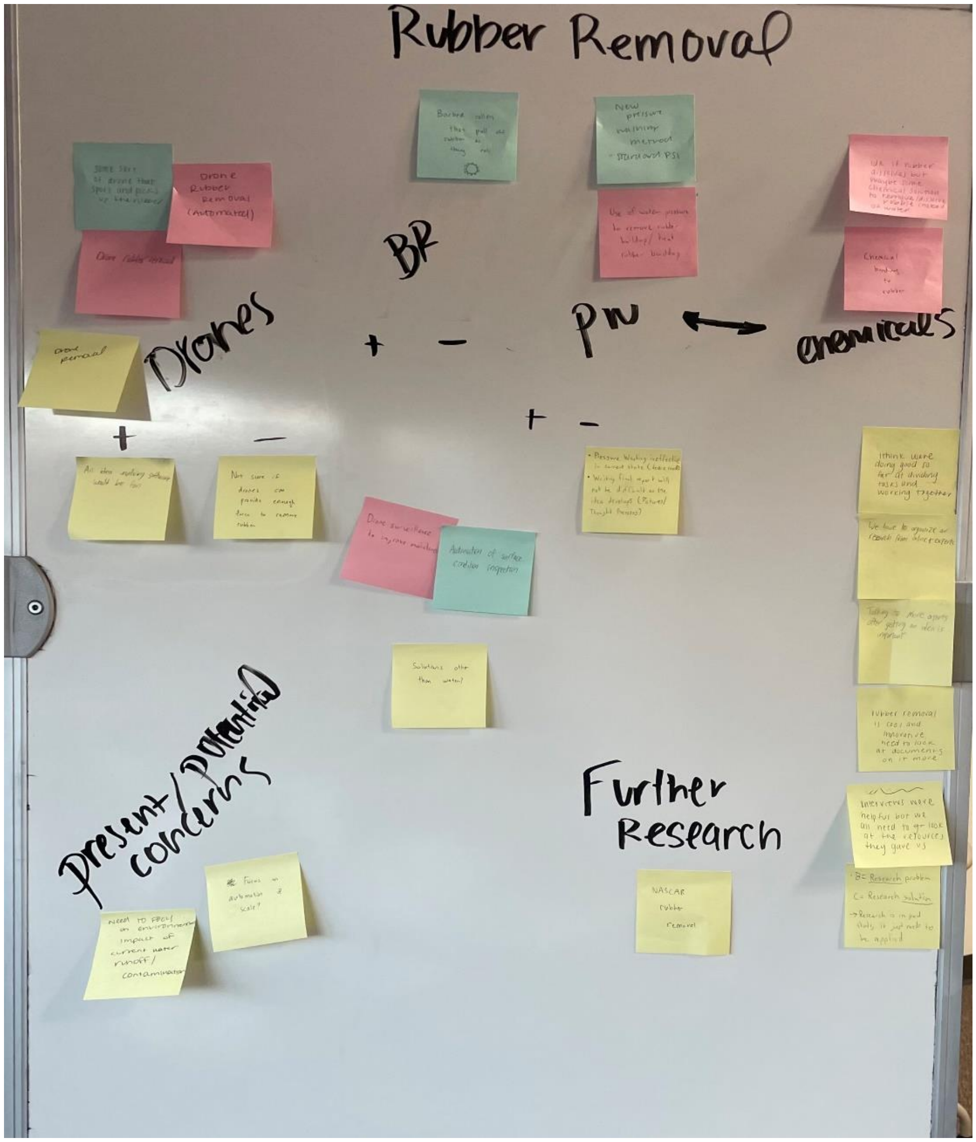
Problem Formulation and Background Investigation

Throughout the design challenge the team was faced with trying to narrow its focus overall and shift the direction in which the challenge was headed. The team often was able to communicate with each other to allow for increased innovation to take root. All having different personality types has allowed the team to build off each other's strengths and weaknesses. After conducting expert interviews with many educated individuals in the field, the team was truly able to gain comprehensive knowledge that helped to streamline each member’s thoughts and more effectively provide direction. With this new knowledge, the team’s problem statement was refined into the following design question, “Given the current difficulties removing rubber from airport runways, what new and innovative methods could be proposed to more efficiently and cost effectively maintain the integrity of runway surfaces through rubber removal?”

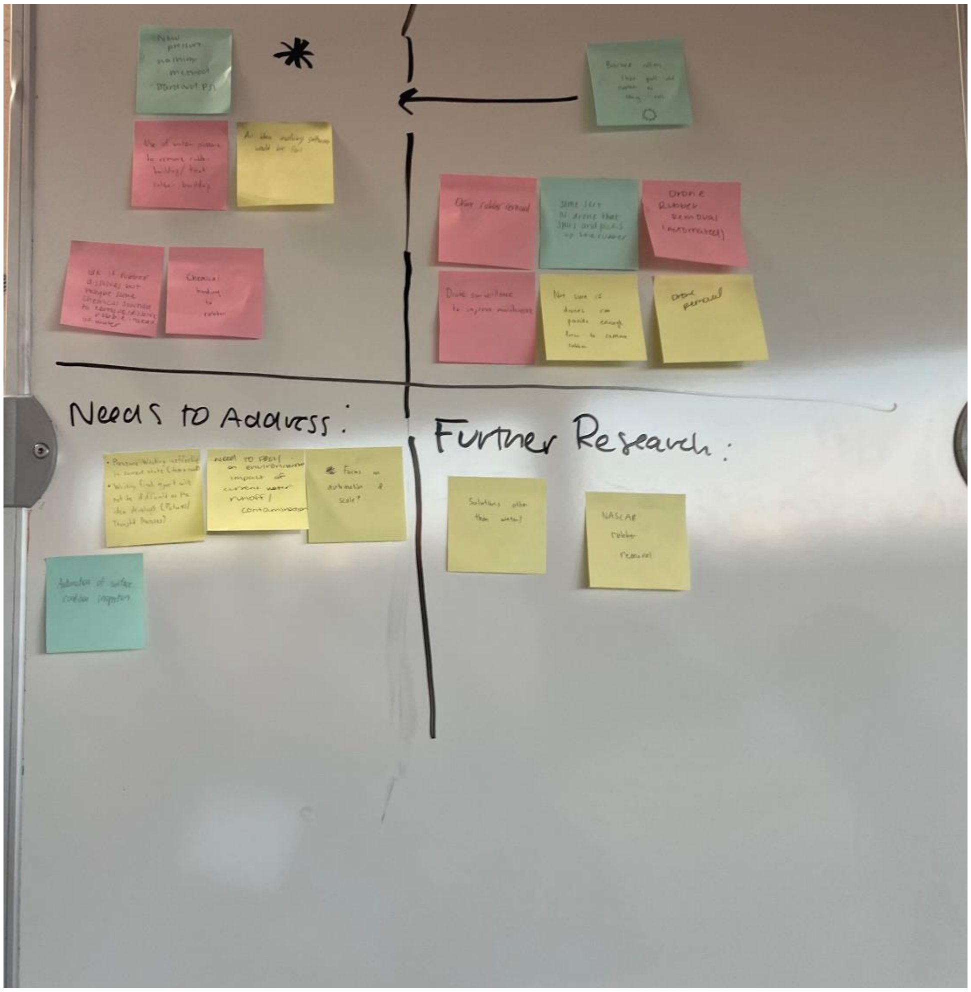
Following the further refinement of addressed problem, the team reviewed research and proposed solutions to understand current approaches to the issue. In the team’s interview with technical expert Dr. David Lange, it was proposed to examine current research and attempt to combine approaches to different areas of runway maintenance. Not only did this allow the team to understand where they stood withing the constraints of the Design Challenge, but it also helped to narrow the scope. A problem that the team faced since the beginning of the challenge. Another issue that arose is that each team member is from a different field of engineering, all of which having different technical expertise. Thus, the team was able to problem-solve and shift focus to a direction that benefited each team member's interest and field of study.

Brainstorming Approach

Throughout the ideation process and narrowing down the scope of the design, the team was able to effectively demonstrate current concerns and ideas throughout a series of different ideation activities. This process was developed in conjunction with and referencing the *Field to Design Thinking*. The first step of this process, Phase I, was "Downloading our Learnings" where the team was able to write down anything that came to mind and anything that has been learned throughout the iteration process thus far. Please reference [Figure 2] and see the yellow Sticky-Notes to see this phase. Following this phase the team transitioned into the next phase, Phase II, by writing down two top ideas so far and the two possible solutions or designs that stood out the most to them. Please reference [Figure 2] red and green Stick-Notes for this phase. Phase III was finding themes behind the ideas presented so far and creating groups and connections and themes between different thoughts. The categories were broken down into four different categories which included: Feasible Ideas, Non-Feasible Ideas, Needs to Address, and Further Research. Please reference Phase III below in [Figure 3].

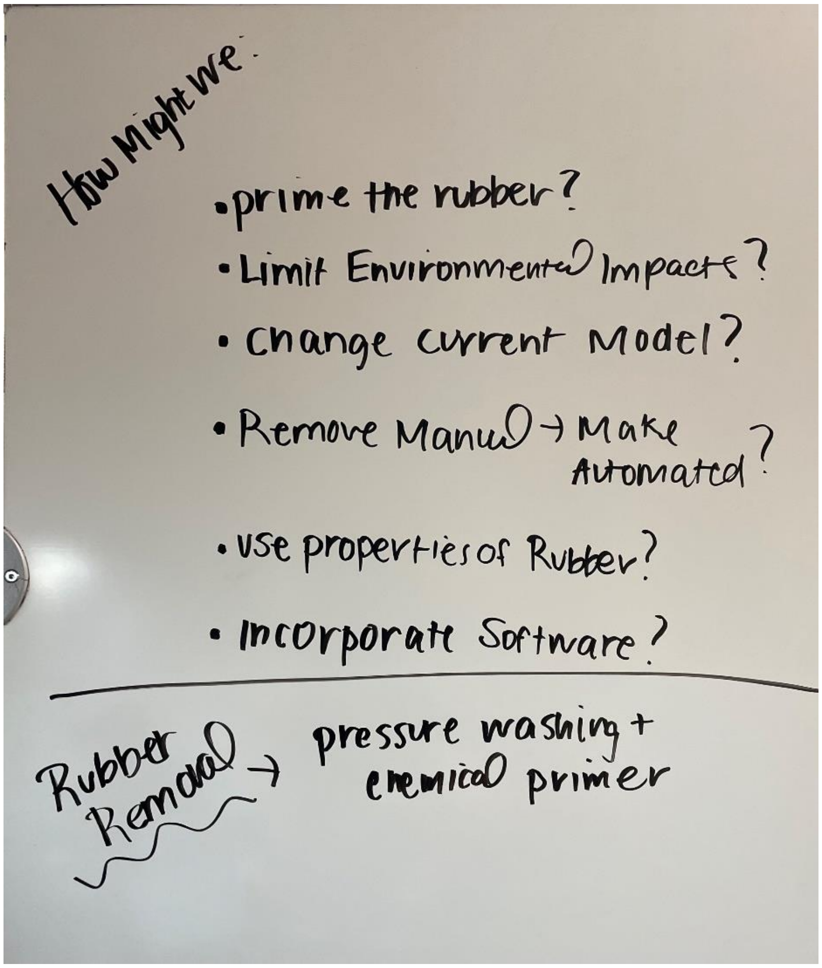


[Figure 2: Initial brainstorming: “Downloading” our learnings]



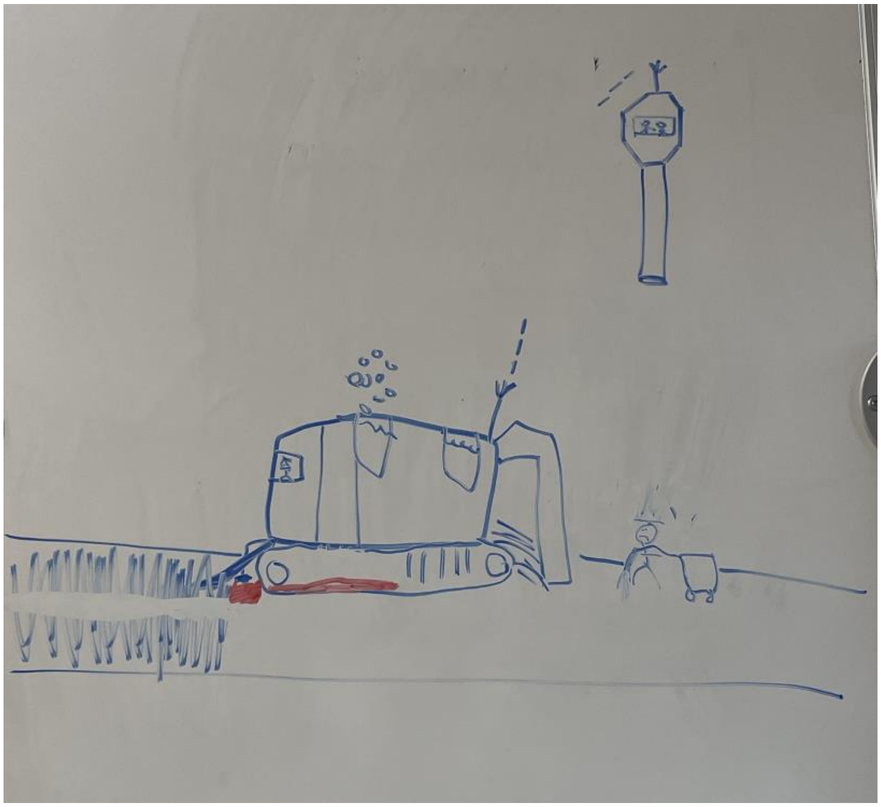
[Figure 3: Brainstorming organization and optimization]

From the previous three different ideation phases the team was able to transition into Phase IV, where "How might we statements" were developed and allowed for the team to consider difficult questions that may have not been taken into consideration before. These statements really allowed the team to see the direction in which the project needed to go and the next steps in the design process. Please reference [Figure 4] for the statements that were developed in Phase IV.



[Figure 4: Further questions stemming from brainstorming]

Following the development of the “How might we” statements, the team was able to develop a more extensive direction in which the project was going to proceed and the design that incorporated everyone’s ideas and solutions thus far. The team incorporated aspects of the game Pictionary and added a part where each team member would add to the picture of the team member before the. During this phase, Phase V, the team worked together to build off of the previous team members drawing added to the board. Team members took turns adding to the drawing until all team members were satisfied with where the design was at. This really allowed all team members to contribute and spark new ideas that the team never considered before. Please reference [Figure 5] for Phase V of the iteration process and the drawing the team came up with.



[Figure 5: Initial prototype design sketch]

Technical Aspects of Design Development

Decision Matrix

These brainstorming activities, particularly [Figure 5], allowed the team to develop four distinct ideas for solutions that would address the task of rubber removal. Each solution possessed unique attributes contributing to its viability for this project. To analyze these and find the best solution, the team made use of a decision matrix with weighted categories to provide an unbiased metric. The team chose categories such as innovation, ease of implementation, ease of prototyping, and personal interest, each given a weight to represent its relative value. Please reference [Figure 6] for the complete decision matrix.

Solution Values	Prototypability	Implementability	Cost Effectivness	Innovation	Enviromental Responsiblity
Weight (1-5)	5	3	1	5	3
Solutions					
Chemical Primer + Water Pressure	3	4.5	3	1	2
Light Sensor-based water pressure	4	2	4	5	4
Light sensor-based automated friction testing	5	5	5	3	3
Automated current friction measuring	3	4	2.5	4	3

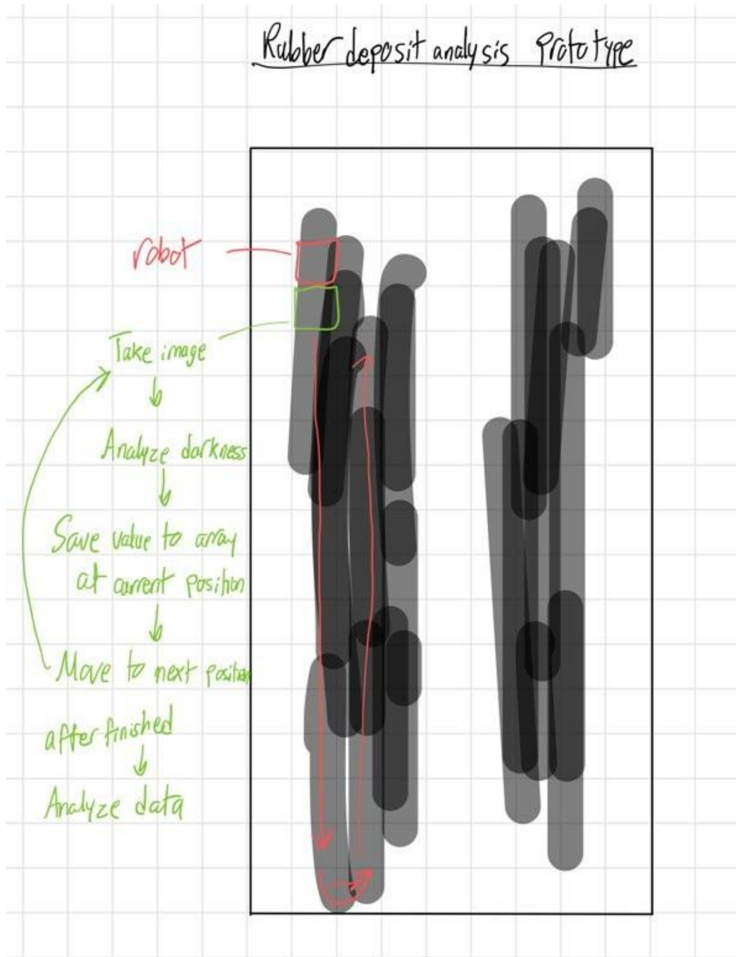
Solution Values	Scalability	Interest	Ethics and Regulations		
Weight (1-5)	2	1	4		
Solutions				Totals	Notes
Chemical Primer + Water Pressure	5	0	1	56.5	We dont like, very hard to innovate
Light Sensor-based water pressure	2	4	4	91	Hardest to implement, solves the biggest problems
Light sensor-based automated friction testing	5	4	4	99	Good and innovative idea, but addresses a lower priority problem
Automated current friction measuring	4	3	3	81.5	Automates current system

[Figure 6: Evaluation of solutions through the decision matrix]

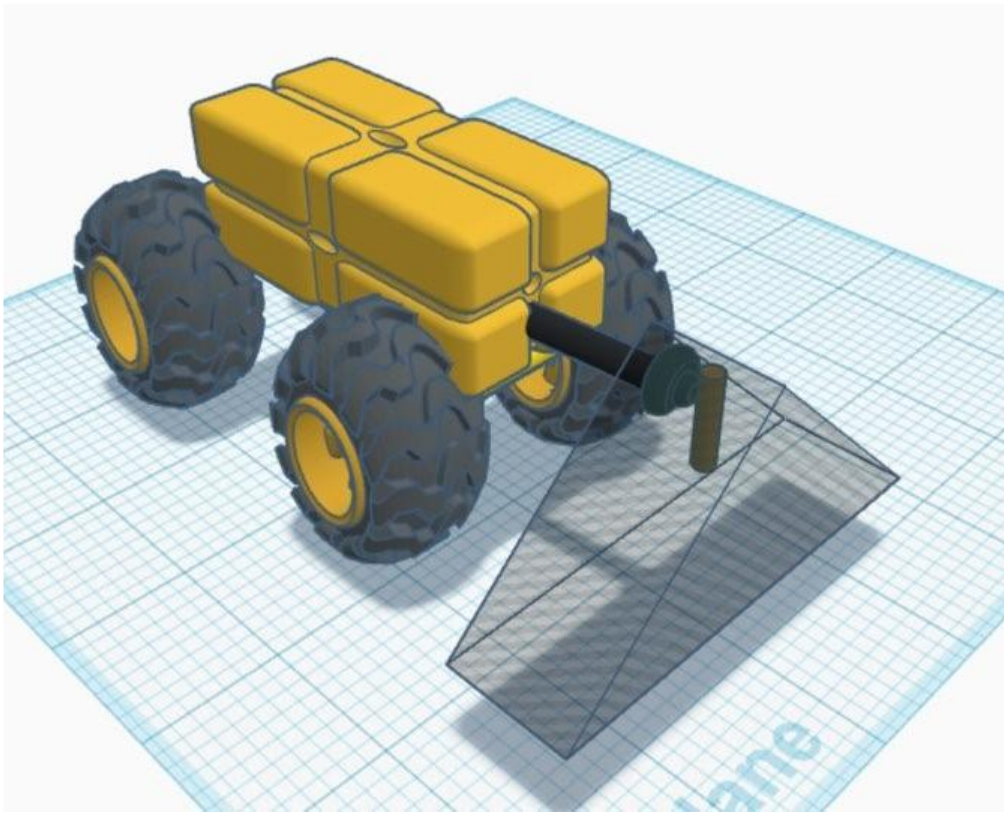
This step left the team with three clearly better options, with one of their original ideas having a significantly lower ranking. The team chose to keep all three of the top solutions as options to present to experts and stakeholders so that they could gain industry insight and make a final decision. These solutions were to: 1) Use cameras on a small robot to automate the process of analyzing the runway surface for rubber deposits; 2) Use cameras and AI to automatically vary the water pressure of rubber removing vehicles; 3) Automate the current manual process of runway friction testing.

Rapid Prototyping

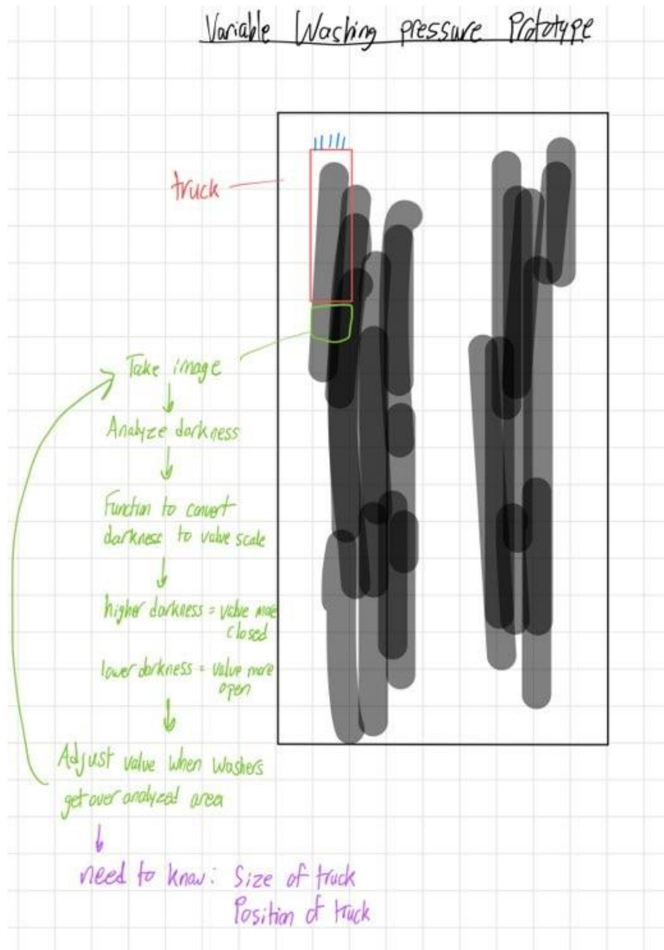
In order to help industry experts, understand each solution during the team's interviews, they made rapid visual prototypes of each by drawing each of the ideas, using CAD software to model two of the three ideas. The team also created simple flowcharts to represent how the software would work at a high level. These simple prototypes also helped the team think through the general idea of each with quick visual designs and high-level, abstracted code, allowing them to predict and prevent future issues while not spending unnecessary time on the prototypes. Please reference [Figure 7] through [Figure 11] 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 prototypes and turn it into a physical device



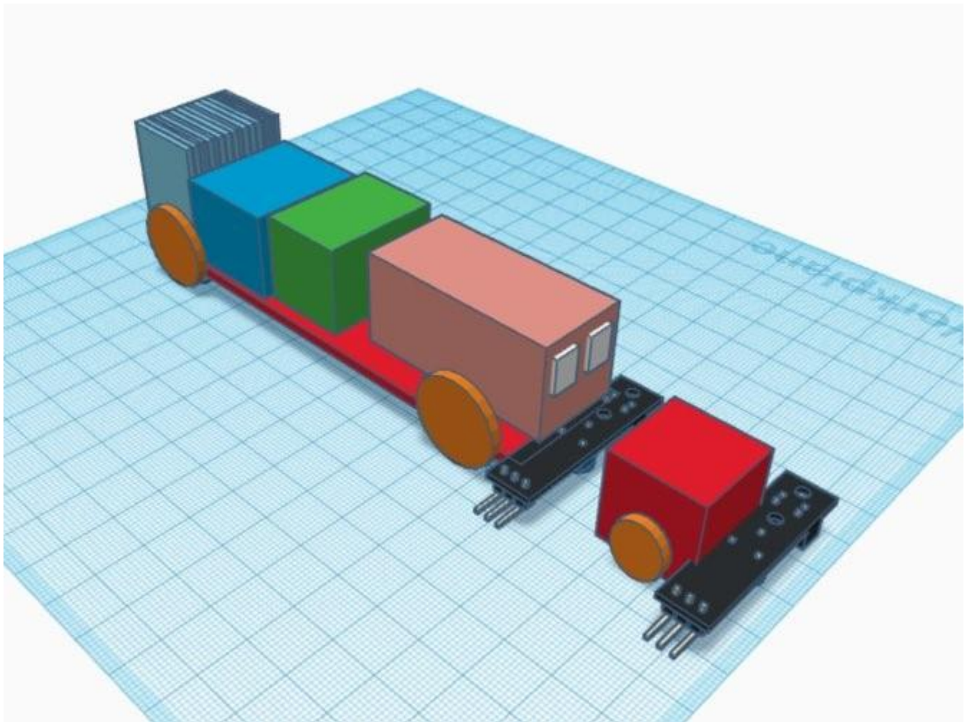
[Figure 7: Prototype 1 Visualization and Software Flowchart]



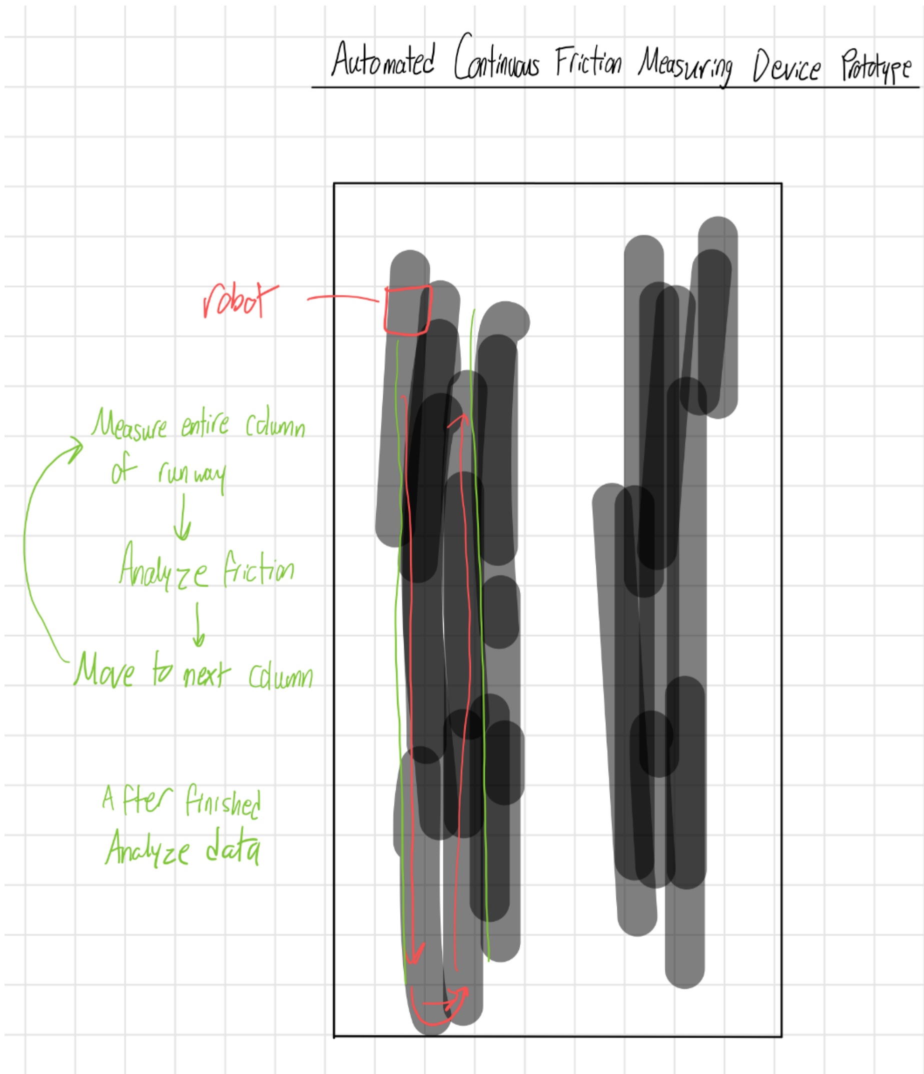
[Figure 8: Prototype 1 CAD Design]



[Figure 9: Prototype 2 Visualization and Software Flowchart]



[Figure 10: Prototype 2 CAD Design]



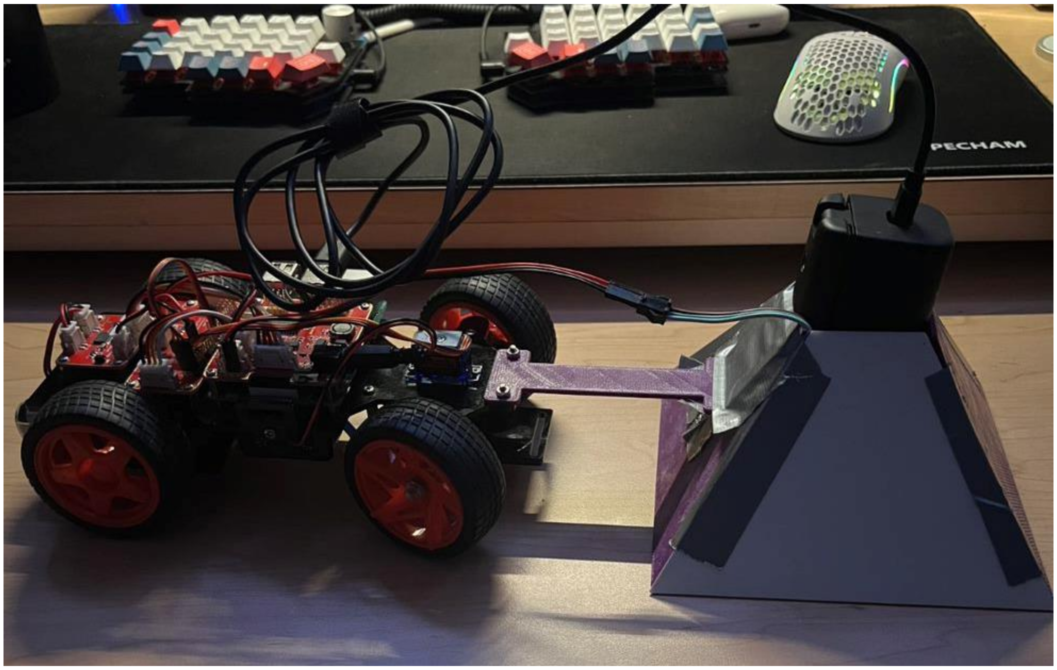
[Figure 11: Prototype 3 Visualization and Software Flowchart]

Stakeholder Feedback

The last step in the rapid prototyping phase of the design process was for the team to interview experts and gain their valuable opinions on each of the designs. The team interviewed the same three experts from the research phase: Gary Mitchell, David Lange, and Kyle Potvin. All three experts held similar stances on the prototypes. They all favored solution 1, the camera-based runway surface analyzer, follow by solution 3, the automation of current surface friction testing devices, and felt that solution 2, the camera-based variable water pressure system, may be too complex to design and implement. One point brought up Dr. David Lange, and a large reason for his support of this idea, is that the simple design of solution 1 would allow for future modularity. He contended that while the current rubber removal process is nearly all manual, including the initial friction testing, it must eventually become automated. Automating this first step would begin that process and allow for many integrations with future automation that would not be possible if the team went with a more complex design. If designed and implemented effectively, it could also save operations crews numerous daily trips to inspect the runway surface.

Final Prototype

With both the decision matrix and industry experts supporting solution one, the team decided to focus the project on this design and continue refining the prototype. The team had an existing prebuilt robotic car which they used as the basis of the hardware to save time so that prototyping could focus on a proof-of-concept version of the software. This car used a Raspberry Pi as the controller for a servo motor that turns the wheels and DC motors to drive the car, as well as providing wireless control via another device on the same network. The kit came with existing software libraries to control the motors, allowing for simple reuse for the team's application of the car. The only major hardware modification made to the car was the relocation of the camera using a 3D printed mount so that it now faced the ground and could take images of the runway. [Figure 12] shows the physical car after it was completed.



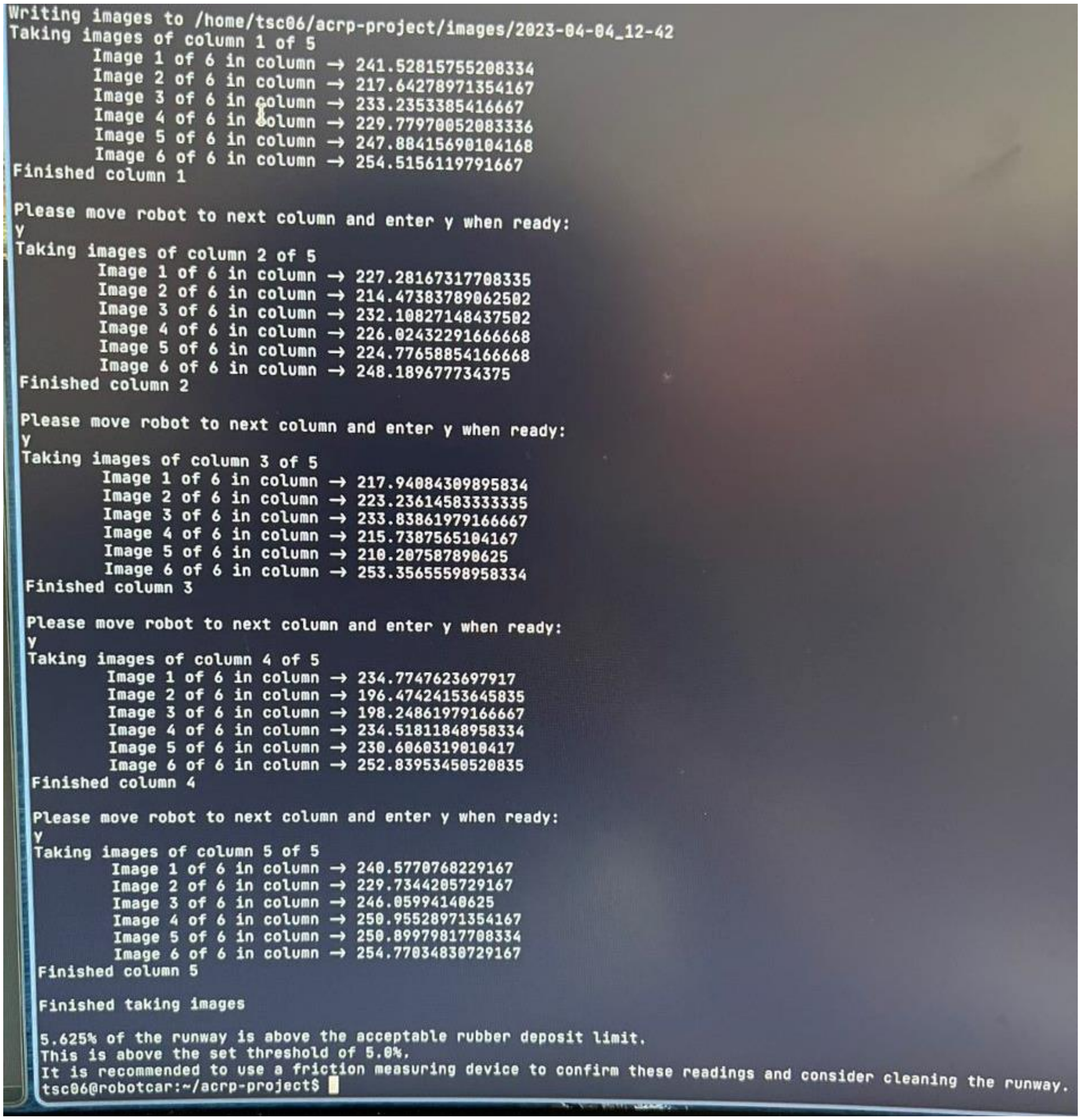
[Figure 12: Completed hardware prototype]

The 3D printed mount was carefully dimensioned so that the opening at the bottom was the same size as the image that will be taken by the camera with its given field of view and height off the ground, minimizing the space taken and weight of the mount. It also shields that image from any external factors including light and weather. Not pictured inside the shield, there are LEDs surrounding the camera to provide a consistent light source so that images taken at different times can still be compared to each other with software algorithms discussed below. This car is a scale model of what the team predicts the final product will be. The final version will be approximately four feet wide by six feet long with a camera shield around four feet wide by two feet long. This makes the prototype a one-eighth scale model, making prototyping and testing quicker and more cost effective as the concept of measuring the rubber deposits does not change based on the size of the device.

The most important part of the final prototype was the software, as this determines if the product idea is feasible and useful. The main challenges of designing the software to run on the car were perfecting the physical movement and implementing the algorithms to analyze the runway surface. Implementing motor control to move the car was easier than expected for the team because of existing libraries to control the motors as well as readily available documentation and examples. The software was designed to be configurable to the runway size and image size so that it could calculate how many images should be taken in each row and column. However, the team ran into issues with inconsistent movement due to low quality parts used from the robot kit that caused variability across tests. They also had to rely on time to estimate the distance moved rather than more precise measurements through sensors. Finally, they found that the 3D printed mount was too heavy for the weak motors to turn, so the robot was unable to turn without assistance. The team plans to incorporate encoders and GPS mapping, as well as using much higher quality parts, in the final product so that all of these issues can be addressed and the vehicle can run accurately and autonomously, however, this initial prototype was still sufficient as a proof-of-concept.

The next step was to implement the surface analysis algorithms in the software. The team used Python to program the robot so that they could use the library OpenCV, a computer vision library that is extremely rich with features and included all of the functions that the team needs. Industry expert David Lange suggested that the team use image subtraction to accurately analyze the surface. This process “subtracts” one image from another by subtracting the RGB value of each pixel in the second image from the RGB value of each pixel in the first image. By doing this, any portions of the image that do not change are eliminated and only portions that have changed are left. The team used this to isolate the rubber deposit buildups by storing a database of images of the clean runway and subtracting the images of the current state with rubber buildup. These images were then inverted because image subtraction had inverted the colors of clean versus rubber covered, and then converted to grayscale so that there was only a single color value for each pixel. Finally, the pixel grey values were averaged across the image to get an average darkness value, where the darker the image was, the more rubber was present. The software has a configurable threshold for this value that represents what darkness value correlates to an unacceptable amount of rubber which would be found by individually working directly with each airport so that they have an accurate value for their own runways.

The motor control and image analysis were combined such that the robot moves across the runway in a serpentine pattern, taking images as it moves. As previously stated, the software can calculate how far it must move before taking another image so that it is taking images of the entire runway without overlap. These images are analyzed as they are taken, and the darkness value is stored in a two-dimensional array that represents the runway broken up into individual images. After completely analyzing the runway, the program calculates how many images were above the acceptable darkness threshold and gives a percentage of the runway that has unacceptable levels of rubber. The airport operators can then use this information to decide when cleaning should be done and more accurate measurements using a continuous friction measuring device are necessary. Please reference [Figure 13] for an example software output, and reference this link to view the entire codebase.



[Figure 13: Example software output]

The team also created a testing surface to imitate a rubber-covered runway, seen in [Figure 14]. They used foamboard as the surface with activated charcoal pastels to represent rubber, which they found to be the closest representation for both visual likeness and texture.

[Figure 14: Device testing surface used to imitate rubber-covered runway]

Even with the physical flaws mentioned above, the team found that the software algorithms did work as expected, signifying that a final product would be able to complete the tasks of accurately estimating the rubber buildup on a runway. For an example of complete test of the prototype, including the vehicle movement and corresponding software output, please see this link.

Future Modifications

This initial prototype serves as a proof-of-concept, primarily for the image analysis algorithms to prove that the design is a viable alternative to the current methods of friction measurement. However, this prototype has a number of flaws that would be addressed in future revisions and for the final product. Firstly, and as mentioned above, the hardware used would be of higher quality and include precise sensors that would allow for precise movement and consistent results during each run. Importantly, this would include implementing GPS mapping so that the vehicle could analyze all runways autonomously without any operator input. The current prototype is also too slow to be used to measure an entire set of runways in one night. The team plans to improve the design so that it can move at a top speed of around 45 miles per hour and include a high quality camera that can take images while the vehicle is moving, eliminating the need to stop for each picture. The team also realized that due to the large width and length of a runway, there are likely some spots around the initial landing point that are generally the most covered with rubber. Thus, it is unnecessary to analyze the entire runway when the troublesome spot can be identified ahead of time and the vehicle is programmed to only analyze those areas. The team predicts this to be about one sixth of the runway, being around half of the length and one third of the width. These changes would allow the vehicle to easily cover the entire set of runways at even large airports in less that the time currently take by manual measuring methods. Finally, the team plans to implement machine learning models so that the analysis improves over time. With these changes, the cost-benefit analysis described below shows that RunwAI is an extremely viable and useful product for all airports.

Safety/Risk Assessment

In order for any product to be viable for use in a possibly high-risk use case such as airport operations, it must have minimal risk under all conditions in scenarios. The team conducted a risk assessment to ensure that no situation or unintended outcome could create unacceptable risk for passengers and personnel. This risk analysis has allowed them to prepare for potential issues and ensure that proper mitigations are in place to prevent the risk of their product's use from being unacceptable.

There are many different safety and risk factors that must be taken into consideration when determining if a product is viable to bring to market. As stated by the Airport Traffic Organization "if a safety issue or hazard is identified through an audit or assessment, [it is important] to document the hazard and identify mitigations" (Safety Management System Manual December 2022, 16). As demonstrated below in [Figure 15] it is important to take into consideration risks that may arise due to design implications and proficient training measures put in place. The top safety measures that must be taken into consideration is getting stuck on the runway, coming into contact with an active plane, improper analyzation of rubber deposits, or possible contact with or deposition of debris. While all these risks are viable in the sense that they must be addressed, with certain mitigation efforts these risks become rather minimal and infrequent in nature. Mitigation includes the insurance of quality checks to the device, proficient training provided to employees and operators, as well as ensuring the device is only ran during inactive runway times. With these mitigation efforts the risks that we have identified, will decrease significantly with time and training.

Likelihood \ Severity	Minimal 5	Minor 4	Major 3	Hazardous 2	Catastrophic 1
Frequent A					
Probable B					
Remote C		§2		2	
Extremely Remote D	§1		1		
Extremely Improbable E		3 §3	§4	4	

Unacceptable Risk
Acceptable Risk with Mitigation
Acceptable Risk

#	**Risk(s)**
1	Getting stuck on runway
2	Improperly analyzing rubber deposits
3	Debree falling off
4	Coming into contact with the plane on active runway
	With Mitigation
§1	Ensure proficient training
§2	Ensure quality checks
§3	N/A
§4	Only run during inactive runway times

[Figure 15: Risk Analysis Matrix]

Projected Impacts of the Team's Design and Findings

Cost-Benefit Analysis

This section summarizes the costs and benefits associated with the project. The total cost to bring this design concept to life has been considered below in Tables 1-3. Following the estimated costs are the benefits that this design solution would bring to the airport industry in Table 4. The cost-benefit analysis (CBA) is a systematic approach to evaluate the potential costs and benefits of the final product. The CBA is important because it determines whether the benefits outweigh the costs. The team was able to estimate the yearly benefit-to-cost ratio and the payback time.

The first phase of design cost, shown in Table 1, is related to the actual cost of producing and installing RunwAI into an airport. The Production, Marketing, Distribution category includes the costs of travel ($1,000), the physical unit ($15,000), as well as delivery ($850) of the product. The product will take 3 in-person visits to be set up, including a consultation, the initial setup, and the final configurations. The costs of the physical unit and delivery were determined by looking at similar existing products. Specifically, the team found that fully electric four-wheeler ATVs are quite similar by design and function to their product. Using these existing mass-produced products, they estimate that their products will fall in a similar price range once production methods and materials are determined, giving the current cost estimates.

A. Production, Marketing, & Distribution				
Item	Rate	Quantity	Subtotal	Remarks
Labor- Manufacturing, Sales, & Installation				
Travel	$1,000	3	$3,000	Will take 3 in-person visits to get product setup (consultation, initial setup, final configurations). Includes cost of transportation (by flight), lodging, and food
Physcial Unit	$15,000	1	$15,000	
Delivery	$850	1	$850	Average delivery cost per unit
Subtotal			$18,850	

[Table 1: Production and Install Cost]

The next phase of the design cost, shown in Table 2, is related to the ongoing yearly cost of providing RunwAI to airports. Most of this cost is from the salaries of additional workers and operators. The software tech support employee costs were estimated by assuming the employees would work 160 hours per year and the onsite tech support labor costs were estimated by assuming the employees would work 50 hours per year. The employee and maintenance costs may need to be adjusted based on the facility's needs. It is predicted that the technician travel expense would be needed 4 times a year. Assuming the product takes 5 hours to inspect all runways, once a week and requires one operator, the onsite operator costs were estimated by assuming 260 hours per year. It is assumed that battery and motor replacement will be needed twice a year, and electronic failure replacement and physical hardware replacement will be needed once a year.

B. Operations & Maintenance				
Item	Rate	Quantity	Subtotal	Remarks
Labor- Personnel & Technical Support				
Software Tech Support	$40/hr.	160	$6,400	160 hours labor per unit per year
Onsite Tech Support Labor	$135/hr.	50	$6,750	50 hours labor per unit per year
Onsite Operator	$50/hr.	260	$13,000	5 hours to inspect all runways weekly
Expenses				
Battery Charging kWh	$0.60	62.4	$37.44	charge 1.2 kWh battery once per use
Battery Failure Replacement	$750	2	$1,500.00	2 battery replacements per unit per year
Motor Failure Replacement	$1,000	2	$2,000.00	2 motor replacements per unit per year
Electronic Failure Replacement	$1,750	1	$1,750.00	1 major electronics replacement per unit per year
Physical Hardware Replacement	$1,000	1	$1,000.00	1 major physical hardware replacement per unit per year
Technician Travel Expense	$1,000	4	$4,000.00	4 site visits/year
Subtotal			$36,437.44	

[Table 2: Ongoing Cost]

To account for Overhead & Profits, an additional 25% has been added to the cost shown below in Table 3. Overall, the estimated 3-year cost for a large-scale airport is approximately $160,000.

C. Cost Summary (for 3 Years)				
Item	Rate	Quantity	Subtotal	Remarks
Cost				
Production, Marketing, & Distribution	$18,850	1	$18,850	
Operations & Maintenance	$36,437	3	$109,312	
Overhead & Profits, 25%	$32,041	1	$32,041	
Total Cost			$160,203	

[Table 3: 3-year Summary of Cost]

Table 4 summarizes the benefits of the project. To determine the benefits, we had to evaluate the costs of the current rubber detection methods. The current method is a fully instrumented pickup truck that uses continuous friction measuring equipment to provide coefficients of friction on airport runways. They use this in order to identify areas with inadequate friction due to a loss in texture from wear and rubber buildup.

The first tangible benefit is reduced vehicle driver hours. The product would eliminate the 10 labor hours a week used to manually test friction of each runway. Assuming the current employees are getting paid $30/hr for 560 hours a year, the product would save $15,600 a year. The second tangible benefit is less vehicle wear and damage. The product reduces the possibility of damage to the operations trucks due to more infrequent use and it also minimizes wear. Assuming 2 instances of damage to the trucks a year costing $2,000 each, savings would be $4,000 a year. Finally, the third and arguably the most important tangible benefit is less passenger injury claims. The product completely removes the chance of injury because manual labor is eliminated. This removes the possibility of worker's compensation claims stemming from friction testing equipment operation, saving approximately $40,000 a year. The intangible benefits are increased consistency in measurements due to automation and many possibilities of future automation and cost savings built around the device's results.

D. Summary of Benefits				
Item	Rate	Quantity	Subtotal	Remarks
Tangible				
Reduced vehicle driver hours	$30/hr	520	$15,600	Eliminate 10 labor hours per week
Less vehicle wear and damage	$2,000	2	$4,000	Minimizes wear and the possibility of damage on operations trucks
Less passenger injury claims	$40,000	1	$40,000	Removes the chance of injury during manual labor
Intangible				
Increased consistency in measurement	xxx		xxx	
Possibilities of future automation and (	xxx		xxx	
Total Yearly Benefits			$59,600	

[Table 4: Summary of Benefits]

Table 5 compares the costs and benefits that are described in Tables 1-4. When comparing the yearly benefit to the yearly cost, the yearly cost-to-benefit ratio for a metro airport over three years for 100 units purchased is 0.89 and the payback time for a metro airport is 1.6 years. This means that the product is approved and that the benefits clearly outweigh the cost. Overall, RunwAI is economically viable and effectively detects rubber on runways.

E. Benefit vs Cost Analysis				
Item	Rate	Quantity	Subtotal	Remarks
Net Values				
Initial Cost	$19,813	1	$19,813	
Yearly Costs	$45,547	3	$136,641	
Total Cost			$156,454	
Yearly Benefits	$59,600	3	$178,800	
Analysis				
Yearly Benefit-to-Cost Ratio			0.875	Benefits outweigh cost
Payback Time			1.4	Years

[Table 5: Cost vs. Benefit Analysis]

Future Impacts

While it is clear from the cost-benefit analysis that this product is a financially viable and commercially useful product on its own, the team also envisions that it could play a crucial part of future automation systems for similar runway analysis and repair tasks. As it stands, nearly all tasks dealing with runway operations are manual processes. However, expert feedback from the team's interviews suggests that there is an industry desire to automate these in the near future. The team's design automates one step of the rubber analysis and removal process, but they believe that through the additions of certain additional sensors, described below, or the integration with existing software, the product would become useful in a variety of applications. These functionalities are not currently supported or designed into the product, but they are directions that further development could move towards.

Foreign Object Debris (FOD) Detection

Foreign Object Debris (FOD) "is any object that does not belong in or near airplanes and, as a result, can injure airport or airline personnel and damage airplanes"(Boeing, Inc.). Thus, FOD must be removed from runways promptly in order to ensure the safety of passengers, personnel, and equipment. In order to be removed, FOD must first be detected. This process can be done in a number of ways including callouts from pilots, cameras mounted on towers, and cameras mounted on airport vehicles (ICAO.int). The team proposes that because its product is designed to efficiently scan the majority of a runway, it would be cost effective to mount an additional camera to the vehicle which would be used as a FOD detection system. Doing this would allow the product to have dual functionality and saves airports from having to invest in a separate system in order to accomplish this task.

Runway Deterioration Detection

Over the life of a runway, the surface degrades for a number or reasons, including the weather, usage, and harsh rubber removal practices. Degradation may include minor erosion of the ribbed runway surface and major issues such as cracks and potholes. All forms of degradation can lead to unsafe runway conditions, possibly exposing passengers and crew to danger. Therefore, it is mandatory to consistently monitor runway surface conditions for any degradation that occurs so that it can be repaired, and to ensure the safety of those using the airport in the meantime. The team strongly believes that the current design of its product, with some additions to the software, would be an effective solution to automatically monitor these conditions. The device already scans a majority of the runway surface, including the most used portions of it, efficiently. This means that the images taken by the camera could also be used to analyze the runway surface for imperfections each time that the rubber deposits are analyzed. Cracks and potholes would be evident in the pictures no matter how much rubber exists, and minor imperfections could be analyzed directly following the removal of rubber deposits. Because degradation occurs over long period of time, the current rubber deposit analysis schedule of once per week would likely suffice for also analyzing surface imperfections, but it would be easy to increase the frequency if necessary. By using this device, airports would not have to purchase a separate monitoring system or pay operations crews to perform frequent manual checks. They also would not have to schedule extra time to analyze these surfaces separate from rubber deposit analysis, minimizing runway downtime.

Variable Water Pressure Rubber Removal

The current techniques used for removing rubber from runways involve the use of high-pressure water, which is applied uniformly to the runway surface regardless of the thickness of rubber present. When removal is performed to areas of the runway with less rubber, The excess water pressure causes damage to the runway surface, removing the typical ribbed texture and leaving a smoother surface. This can have a negative effect on the surface friction, which could lead to unsafe conditions. With further development with machine learning, the team's product could provide a viable solution to this problem. In its current state, the product can identify and collect data on the surface density of rubber deposits on the runway. The team believes this data can then be used to provide instructions to a device that would vary the water pressure accordingly. The water pressure could be varied in various ways, including adjusting the speed of the motor or the nozzle size of the washing device. This would ensure that the only the necessary water pressure is used on a given spot on the runway, minimizing surface damage. As the product continues to learn through iteration, the device would be able to optimize rubber removal efficiency for both cost and time. Airports would be able to benefit from lower long-term maintenance costs and increased pavement lifetime.

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

Dr. David Lange

- Professor University of Illinois Department of Civil and Environmental Engineering

Mr. Kyle Potvin

- Vice President at Applied Pavement Technology

Mr. Gary Mitchell

- Vice-President at Airport and Pavement Technology American Concrete Pavement Association

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, this project not only provided real world experience in research and product development, but also how to effectively work as a team in a professional setting.

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

A challenge that the team faced was selecting a final prototype to focus on. The team had designed 3 main prototypes all regarding rubber detection and removal, and had a hard time deciding on which one to choose. Therefore, it was decided that the team would meet with the industry experts again and get their opinion on the prototypes. This allowed the team to get a different perspective and come to a decision on selecting a final prototype.

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

The team started by picking a few areas of interest and relied heavily on industry experts to point towards the most pressing issues in these areas. The team felt that this was the most efficient way to find the problems that would make the biggest difference being solved. After their input, the team was then able to do further research into what it may take to solve these problems and choose one that would be feasible to address with a solution, with limited resources and time available. Using the expert's information and the team's own research, multiple problems were able to be narrowed down to a specific problem and the team was able to move onto brainstorming solutions.

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

Participation by industry in the project was extremely useful. The industry professionals gave insightful information and advice that helped to narrow down the project scope.

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?

By working on this project, the team has learned a lot about leadership, teamwork, communication, time-management and problem solving. This project gave the team great experience in furthering each member's networking skills, product development, and how to successfully enter the workforce as an active team member.

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