

2015-2016 ACRP University Design Competition

Title:

Drone-enabled Foreign Object Debris (FOD) Removal System in *ad hoc* Situations

Design Challenge: Airport Operation and Maintenance

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EXECUTIVE SUMMARY

Foreign object debris (FOD) can cause significant problems at airports – even the smallest piece of debris can pose major hazards to safe airport operations. Although intensive FOD monitoring and removal strategies are already implemented, an estimated \$4 billion from related damages are recorded annually. Exploring improved preventative measures is essential to reduce financial risks and ensure safer air travel.

In this study we propose a novel system that will introduce unmanned aerial vehicles (UAVs-- also referred to as unmanned aircraft systems (UASs) or drones --the terms will be used interchangeably) to be tasked with removing FOD in select situations. When implemented, the proposal will increase the safety of airport operations while maintaining efficient handling of high-volume air traffic. We recommend this system to work as a supplementary tool to existing maintenance and FOD removal strategies. From the standpoint of feasibility and safety concerns, this proposal will not explore options for a fully autonomous system.

The drones will be dispatched in situations where this method will be superior to pre-existing methods (ground vehicles and personnel dispatchment). Potential scenarios include occurrences when (a) debris is sufficiently small, common and isolated, (b) debris is too far from a maintenance vehicle or station, and (c) when high-speed removal is required.

The main goals of the design will be increased safety, reduced financial risk, potential increase in airport capacity, and further innovation in airport operations and UAS technologies. Through a case study and financial analysis of the commercial viability of the idea, we believe this proposal has great potential to be implemented in the near future.

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1 PROBLEM STATEMENT

Foreign object debris (FOD) can cause significant problems at airports – even the smallest piece of debris can pose major hazards to safe airport operations. Although intensive FOD monitoring and removal strategies are already implemented, many FOD-related damages are recorded annually. It is of essence to explore improved preventative measures in order to reduce financial risks and ensure safer air travel.

In this study we introduce a drone-enabled system tasked with removing FOD in select situations. When implemented, the proposal will increase the safety of airport operations while maintaining efficient handling of high-volume air traffic. We recommend this system to work as a supplementary tool to existing maintenance and FOD removal strategies. From feasibility and safety concerns, this proposal will not explore options for a fully autonomous system.

2 BACKGROUND

In 2000 the historical Air France Concorde crash killed all 109 people on board and 4 on the ground as a result of foreign object debris on a runway [1]. Following this tragic event, airport officials worldwide have strived to improve debris detection and removal systems to avoid similar future runway occurrences.

Foreign object debris (FOD) is classified as “any object, live or not, located in an inappropriate location in the airport environment that has the capacity to injure airport or air carrier personnel and damage aircraft” [2]. Common sources of debris currently found on the runway include: parts of airport infrastructure that has deteriorated; miscellaneous items fallen off from the aircraft, such as luggage tags; and random objects, such as plastic and polyethylene materials that have landed on the runway via wind or environmental conditions. Debris can vary in size and type, from a small golf ball to a piece of aircraft as shown in Figure 1.



Figure 1: Example of FOD found on runways. [3]

Boeing has estimated that FOD on the runway results in approximately \$4 billion a year in damage costs [2]. To repair a single damaged engine can range anywhere from \$250 thousand to \$10 million, depending on the type of engine [4]. The result of FOD damaging aircraft levies heavy tolls on the airlines that must repair their aircraft. FOD on the runway also imposes high

costs to airports that make revenue from the operations run per day.

In efforts to improve runway safety airports have implemented intense FOD prevention programs. Technologies such as power sweepers, vacuum systems, and jet air blowers collect and remove FOD using mechanical means (Figure 2a). Non-mechanical devices, such as friction mat sweepers, magnetic bars, and rumble strips, are used, as well (Figure 2b).



Figure 2a (left): Model HSP Airport Runway Sweeper. [5]



Figure 2b (right): FOD-Razor™ Airport Runway Sweeper, single mat version. [6]

As for FOD detection systems, new radar sensor technologies have been implemented in select airports. These sensors complement visual human observations from vehicles on the runways or from the air traffic control tower, further improving detection accuracy.

This paper presents the idea of combining these emerging technologies into one system that would provide the service of both detecting and collecting foreign object debris in select situations. This new innovative system of incorporating an integrated drone system would vastly reduce runway closure time as well as accurately remove all debris off the runways, maximizing safety and airport operations.

3 LITERATURE REVIEW

Various ground-based FOD removal and detection equipment are currently used to maintain safe and efficient runway operations at airports. In this section detection system and unmanned aerial vehicle (UAV) applications that could be useful in achieving the drone-enabled FOD removal idea are reviewed. Additionally, two relevant anti-FOD proposals will be critiqued.

3.1 FOD DETECTION

A number of FOD detection systems already exist at some major airports. A notable system implemented is the “FODetect” solution at Boston Logan International (BOS) Airport. Developed by XSight, this technology can detect debris through a system of camera/sensors mounted on airport lighting fixtures (Figure 3). “FODetect” integrates sensor scanning capabilities with a software platform to scan, detect, alert, and analyze the occurrences of runway obstructions. Sixty-eight electro-optic and radar sensors are placed at 200-foot intervals parallel to BOS’ busiest runway [7]. These sensors scan the runway in 60 seconds and can find debris as small as an aircraft rivet. When a sensor detects something, information (such as an alarm message and video footage) is sent to an operator so crew can be dispatched to remove the foreign objects, such as debris and birds [8]. FAA studies have concluded this system as

effective in being “able to detect objects of various sizes, shapes and materials on runway surfaces and perform satisfactorily in nighttime, daytime sun, rain, mist, fog, and snow” [9].

Other technologies are compared in Table 1. The “Tarsier Radar” [10] at Theodore Francis Green State Airport (PVD), Providence, RI and “iFerret” [11] at Chicago O’Hare (ORD) International airport install cameras attached onto towers to closely monitor conditions on runways. The “FOD Finder” [12], also at ORD, mounts sensors on the roof of airport vehicles, and obstructions are detected by driving around the airport taxiways and runways. These solutions are less extensive than the full sensor system, such as the “FODetect” technology, and easier to implement. The “FOD Finder,” especially, is considered as a low-cost solution.

Table 1: Notable FOD detection technologies. [13]

Detection Systems	Instrumentation	Summary
FODetect	<ul style="list-style-type: none"> • Millimeter wave radar • High resolution camera 	Hybrid system of unique integrated optic sensor with NIR illumination and a millimeter-wave radar sensing technology in Surface Detection Units (SUDs) along the runway.
Tarsier Radar	<ul style="list-style-type: none"> • Millimeter wave radar • High resolution camera mounted on rigid towers 	Millimeter wave radar is used to give uninterrupted coverage of the runway, while object identification is enabled by a powerful day and night camera system, cued onto the object automatically. Camera provides live footage once an FOD has been identified to facilitate its classification and removal.
iFerret	<ul style="list-style-type: none"> • High resolution camera • Mounted on rigid towers 	Intelligent vision-based FOD detection system providing real time, automated detection, location, classification, and recording.
FOD Finder	<ul style="list-style-type: none"> • Millimeter wave radar • Multi-axis infrared camera/video sensor tracking ball mounted on roof of vehicles or fixed to any flat surface 	Mobile/fixed millimeter wave radar that locates FOD in a single pass with a 600 ft. diameter (wide) radar sweep covering the full width of the runway, its shoulders and approaching taxiways/high speed turnoffs.

Implementing these surveillance systems comes with a price tag. These technologies, however, are not as overpriced as one may assume. For instance, the Xsight system at BOS airport costs \$1.7 million to install, with \$900,000 covered by the FAA. Naturally, pricing depends on the length of the runway. Runway 9/27 (7,000 feet) at BOS is relatively short, and “\$5-6 million is a good ballpark for longer runways” [8]. Nonetheless, the FAA reports an annual estimate of \$4 billion to correct FOD damage [4]. Especially at busy



Figure 3: FODetect sensors at Boston Logan Airport. [14]

airports, spending to implement these types of systems seems to be a beneficial tradeoff to reduce economic losses caused by debris. Indeed, from an operational standpoint, XSight claims that the FODetect increases runway capacity, adding up to four slots per hour [15].

3.2 DRONES

Drones are getting increasing attention for future widespread use. Notable advancements in this field of study are currently occurring, enabling drones to be more easily used as elements in an innovative FOD removal system.

For instance, UC Berkeley’s Center for Collaborative Control of Unmanned Vehicles (C3UV) is a leading research center in the field of drone operations. The Center explores the technical feasibility of drones in complex maneuvers such as FOD detection and removal. Since runway surfaces are flat, have no obstructions, and are surrounded with an abundance of open space, drones possess high applicability for extensive debris identification. An extension of this capability is C3UV’s development of a Collaborative Sensing Language (CSL) on a Graphical User Interface (GUI) platform. Enabling real-time network communications between drones and the control interface, these tools should be capable of accurately locating a target on the runway.

The sensor-centered system discussed earlier is not the only strategy in implementing automated FOD detection; drones themselves can also locate targets in a sophisticated manner [16].

Developments in the mechanical aspects of drones provide promising outlook as well. Importance is stressed to ensure that the drones operating to remove FOD will not become FOD themselves. Swiss-based company, Flyability, is developing “Gimball,” which is “the first ‘collision-tolerant drone,’ utilizing a rotating spherical outer cage [...] designed to enter hostile environments [...] and navigating restricted areas” [17]. As the winner of the “Drones for Good” international competition in February 2015, outlooks on improving upon the fragile structure of drones seems promising in the future.



Figure 4: MD4-1000. [18]

High-speed and accurate payload pickup maneuvers are also vital. These maneuvers can be enhanced by using controlled manual quadcopters: this can ensure the best attainable accuracy and grabbing mechanism of the target (R.

Sengupta, personal communication, February 27, 2016). In today’s market, there are just a few high-end quadcopters capable of performing safely in any weather conditions. The MD4-1000 (Figure 4) from Microdrones is a good example: it has high performance capabilities in any weather condition [18].

Another contrasting yet promising idea is a prototype for an “eagle claw” drone (Figure 5) that can pick up payloads at high speeds. A team of researchers of the GRASP Lab at the University of Pennsylvania have designed a drone to grasp and retrieve objects at high speeds.

The mechanism mimics that of aerial predators to achieve an efficient method of picking up a target, compared to a “traditional” image of drones stopping and hovering while trying to grasp something, wasting fuel and time [19]. The fusion of these concepts can be significant in attaining both accuracy and efficiency in the removal of runway debris by drones.

Although advanced sensor and UAV technologies already exist, this is a research area that may be further integrated in many different ways. Developments in FOD removal operations is no exception: our proposal promises to become an innovative and beneficial investment.

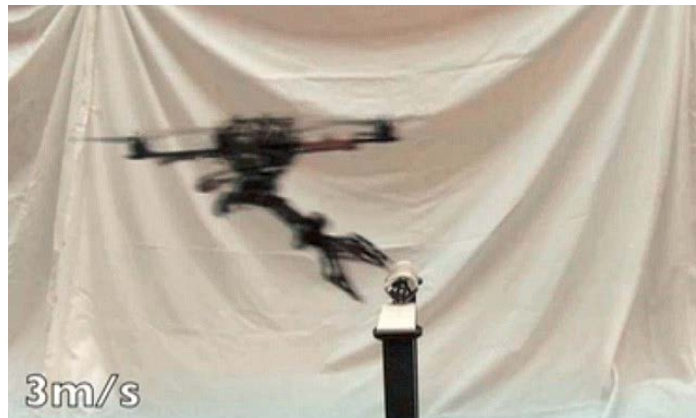


Figure 5: Prototype of eagle claw drone. [19]

3.3 CRITIQUE OF EXISTING PROPOSALS

Recent research has explored FOD removal strategies using automation techniques and robots. This section discusses the limitations of traditional land-robots, as well as the risks and infeasibility of a full-automation system.

In 2012 a group of undergraduate mechanical engineers from Tufts University designed a new robotic automated debris collection system, which they have named FODHippo. Similar to our design, the design goal is to integrate existing detection technologies with the FOD retrieval system, while improving upon safety and maximizing runway capacity. This project ideally eliminates the need for personal human interference to retrieve FOD directly from runways. Based on robotic prototypes, the target round-trip retrieval time of FODHippo system is 3

minutes, which is significantly lower than the estimated standard today of roughly 10 minutes per FOD removal [20].

Likewise, our FOD removal design aims to increase runway safety while creating economic benefits. Both of the ideas employ remote-controlled machinery; however, drones will be superior to land-based robots from an efficiency standpoint. Drones are able to fly and retrieve the FOD swiftly from the ground by taking the shortest possible path, eliminating any sort of ground obstacles that might appear for FODHippo robots. Furthermore, as the FODHippo is a ground vehicle, it has a higher chance of creating FOD itself, whether it be from dropping debris during transport, wear and tear of the machine from friction, higher chance of crashing into obstructions, or parts of the robot falling off. As assessed by Boeing, the benefit would be the drone's ability to approach the debris on the runway from over the grass where a vehicle cannot operate: anything that keeps a vehicle off a runway will improve safety (B. Bachtel, personal communication, April 19, 2016).

The more significant issue is that any fully automated system can have substantial risk in malfunctioning, especially in rare conditions such as extreme weather conditions. Removing human factors from the debris removal process, where each occurrence is unique, will create significant safety concerns.

A concept of multi-robot coordination for autonomous runway FOD clearance was discussed by Öztürk and Kuzucuoğlu [21]. Much like the FODHippo system, their study also suggests an entirely automated system with no human intervention. To avoid all technological risks or accidents, however, the drone system should be managed and operated by UAS professionals who will be controlling the drone from afar making sure that every removal step is completed without any further complications that could potentially create a hazard.

Combining our research findings with the existing literature, our proposed drone FOD removal system seems to overcome some of the limitations found in other removal strategies. As presented in this study, our design is targeted to be the safest and most reliable FOD removal system of all known, existing proposals.

4 DESIGN DESCRIPTION

As discussed in our preliminary research, having an effective FOD removal strategy is extremely important in securing safety of runway operations. Many proposals, such as the FODHippo and a multi-robot coordination approach, provide initiatives to combat risks associated with FOD; however, they fail to take into consideration many factors required for a feasible and successful system. This paper presents an innovative idea of a drone-enabled system tasked with removing FOD in select situations. When implemented, the proposal will increase the safety of airport operations while maintaining efficient handling of high-volume air traffic. Contrary to other ideas, we recommend this system to work as a supplementary tool to existing maintenance and FOD removal strategies. From feasibility and safety standpoints, this proposal will not explore options for a fully autonomous system.

4.1 RADAR

Integrating sophisticated FOD detection technologies within the system is vital for the successful implementation of our design proposal. Before the drones will be considered to be dispatched, the FOD removal team division will closely monitor runway conditions, and look for any alerts arising from the radar system. As explained previously, technologies, like the FODetect solution at BOS, will provide accurate information regarding potential obstructions in

a timely manner. Using the advanced radar technologies will provide accurate information to the debris removal team, so they can make correct decisions accordingly.

4.2 DECISION PROCESS IN DRONE DISPATCHMENT

Once a piece of debris is located and identified, the FOD removal team division will determine its next actions. Unlike existing proposals, which assume dispatching a robot for all scenarios, a decision must be made whether or not the debris will be removed by drone (new method) or ground vehicle (traditional method). The rationale is that it will be unrealistic to have UASs (or any type of automated robot, in that sense) address every single obstruction and replace regular maintenance schedules: this would require an unrealistically large fleet for the option to be financially and systematically viable. Although UAS research is an emerging field with much advancement in recent years, the application of drones to FOD removal is still in uncharted territory. We anticipate that our proposed design will facilitate further explorations of this proposal.

Nonetheless, the drones will be useful in removing FOD in *ad hoc* situations. Figure 6 displays a simplified flowchart of the specific procedure in deciding when the dispatchment of the UAS will be acceptable. The debris removal drones will be dispatched in situations where this method will be superior to pre-existing methods (such as power sweeping and manual removal). Potential scenarios include occurrences when debris is sufficiently small, common, and isolated; debris is too far from a maintenance vehicle or station; and when high-speed removal is required (such as when a runway cannot be closed down due to an oncoming landing, shown in Figure 7). UASs can provide several advantages to FOD-- most notably their swiftness and short overall time requirements for removal. The limitations are that only one piece of FOD can be removed by one machine at one time and that some debris may not be suitable for pickup

(because of size, weight, texture, for example); these cases would require normal vehicles to be dispatched.

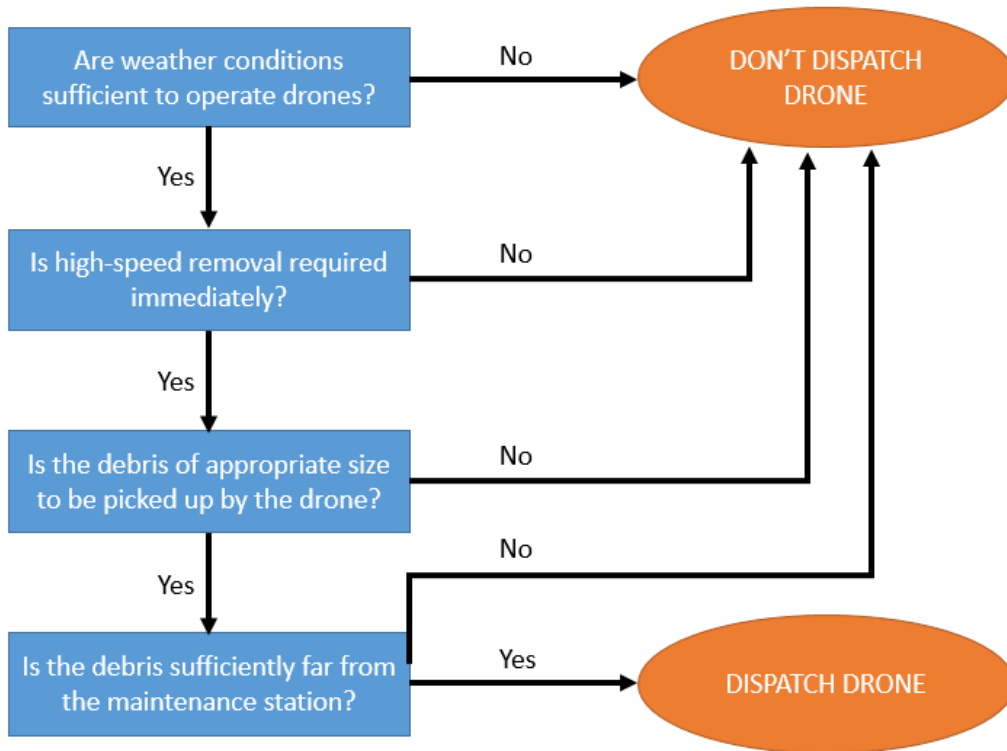


Figure 6: Flowchart of decision-making process of dispatching a drone for FOD removal.

As the proposal assumes a holistic approach, other factors may be considered for dispatchment as well. Weather will be a significant element: in times of poor visibility conditions (such as rain, fog, or snow), operating the drones may not be efficient; rather, they may very well be an additional hazard to airport operations. Furthermore, during congested times of the airport, aircraft will be obstructions to the UASs' paths. Additional cases of obstructions, like the aircraft during peak hours, must also be considered in the decision-making process.

4.3 OPERATING THE DRONES

To reiterate, all UAS-related decisions will rely heavily on heuristics. Although advanced technology already exists, maintaining a human element in the process will be reassuring to airport officials, pilots, and passengers alike. Air transportation is the safest mode of

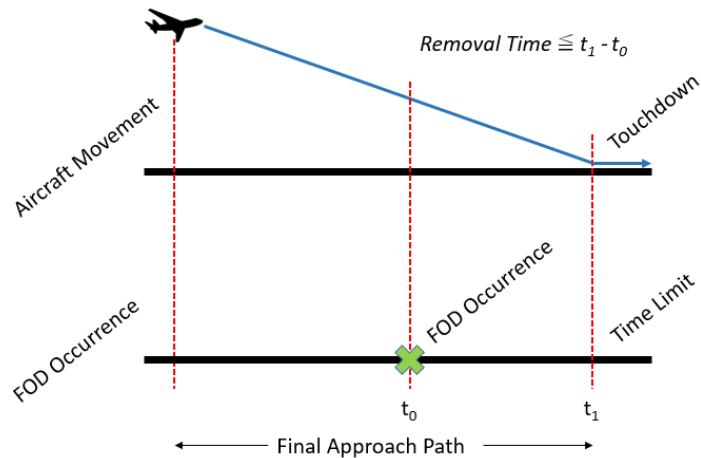


Figure 7: A potential scenario of high-speed FOD removal. The drone will allow for quick removal of the debris without interfering with planned landings.

transport (J. Rakas, personal communication, August 25, 2015), so it will not be worth the risk to convert the entire system to an automated system.

With this fact clarified, if the requirements are fulfilled and a drone removal procedure is approved, the drone pilots will be in charge of controlling and monitoring the process. Piloting the drone will be a “teleoperating” process: because UASs are unmanned, maneuvering procedures will be performed off-site in a distant control room. Drone operations are very human-intensive. Current FAA requirements mandate UASs to be operated by two navigators: the pilot in command (PIC), who will perform the maneuvering procedures, and the visual observer (VO), who will fly the drone through the nose (and use the attached camera to interpret the surrounding environment) [22]. For additional safety considerations, “UAVs @ Berkeley” recommends using a third person, who will oversee both pilots (D. Hooper, personal communication, April 7, 2016). Flying an aircraft requires a minimum of two operators, who are

the pilots and the air traffic control (ATC) personnel; drones are similar in this sense that a multi-faceted team must be formed to use the UASs efficiently.

As one can deduce, the new proposal requires close cooperation. Because drones must travel safely in the airport's airspace, the ATC must be responsible to ensure unobstructed travel. Three officials should be tasked with operating the drone: the manager and the two pilots will sit with the FOD detection and removal team, with the manager keeping constant contact with a designated ATC official sitting in the tower (Figure 8). Initially, maneuvering drones might seem to be very labor-intensive and inefficient; however, it is assumed that the strict drone removal dispatch requirements (only in *ad hoc* situations) will not cause too many issues. Furthermore,

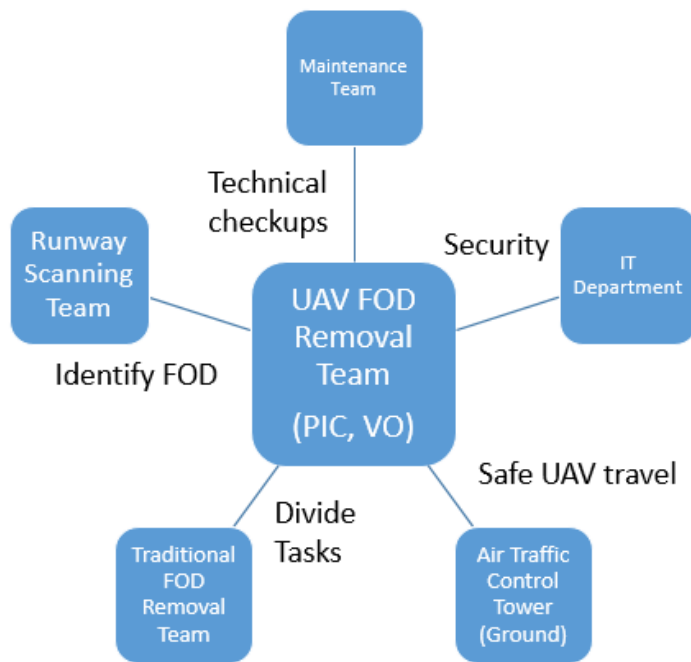


Figure 8: Cross-departmental collaboration scheme of UAV-enabled FOD removal.

advancements in control technologies and safety may reduce strains experienced during the process.

Although constant communication between the UAS team and the ATC is essential, getting support from other departments is vital as well. As depicted in Figure 8, the ATC,

maintenance team, runway scanning team, traditional FOD removal team, and the IT department are important entities that will provide the drone control squad with information and services that

are valuable in ensuring smooth operations. Airport officials will be tasked to design a scheme that holds all related players accountable.

4.4 TECHNICAL ASPECTS OF DRONE FLEET AND SYSTEM

The airport will maintain a fleet of drones to be used for the selective FOD removal procedures. The number of drones to be implemented will depend on various factors such as airport capacity, runway quantity, length, and locations, and frequency of FOD. We can assume that a small number of drones will be installed at each drone station.

Drone stations, which will be the “bases” where the drones will be dispatched from and return to, will be strategically placed around the airport. These stations will be situated so that all areas of the airport can be accessed in a reasonable amount of time. Figure 9 outlines a method that airports can use to compute the optimal number and locations of drone stations to be placed on its site. First, historical data of all FOD occurrences is collected. All of these occurrences will be labeled as a specific instance (point), and information on latitude, longitude, and debris type will be recorded. This information will be entered into a computer algorithm in the form of a p -median problem, to minimize the aggregate distance from the potential station location to each FOD occurrence. The model will be run for various scenarios of p , which is the number of stations to be built at the airport. The problem can be formulated as an integer linear program and solved using software such as Gurobi, CPLEX, and Lindo. Alternatively, using the Network Analyst tool in the ArcGIS interface will allow for easy visual representation of the results. Once a set of solutions is obtained, sensitivity analysis should be conducted to determine the optimal plan of locating the stations, taking into consideration the number of stations, cost, overall distance required for removal, and other miscellaneous limitations. Specifically, tradeoffs should

be considered (cost of building an additional station vs. distance able to be minimized as a result of this) to determine the optimal number of stations to be built.

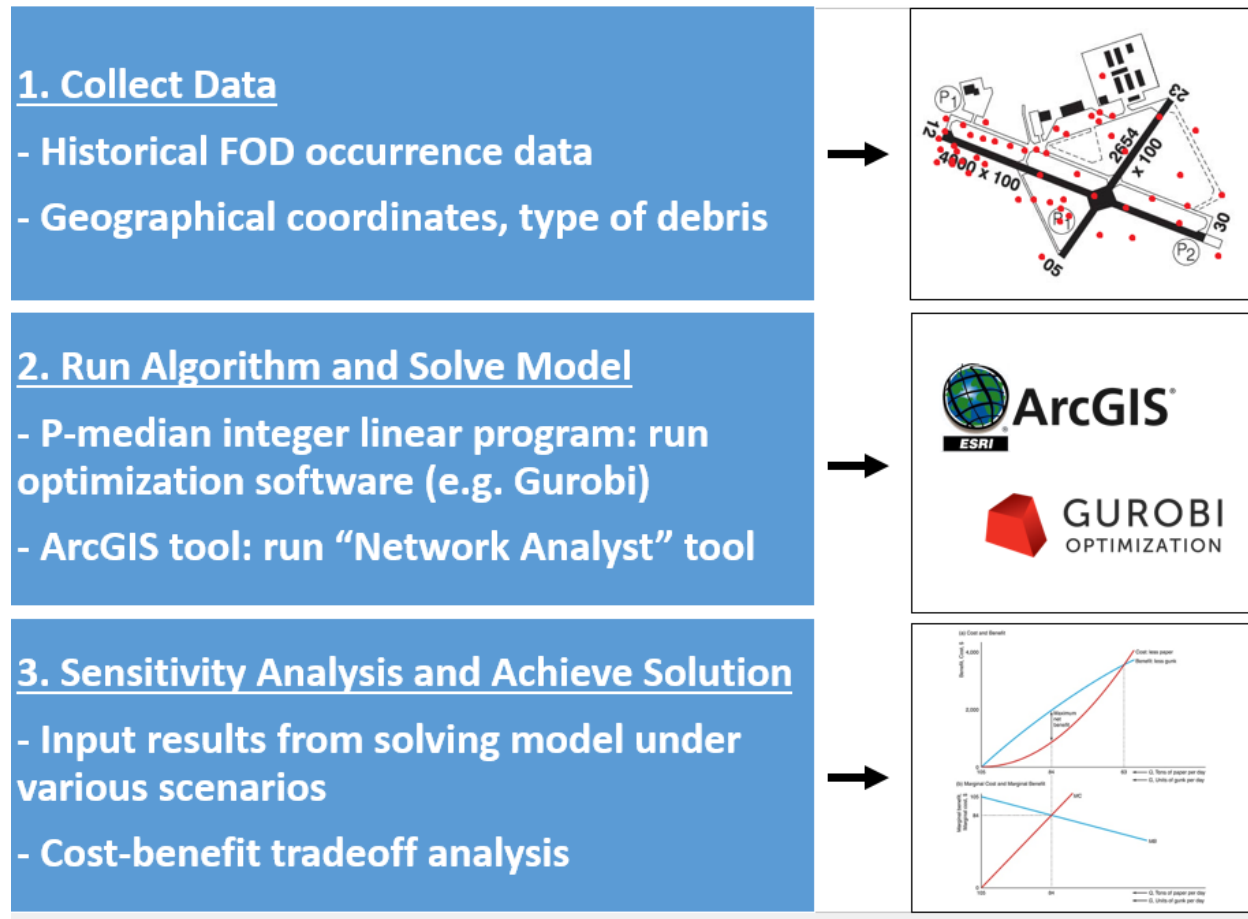


Figure 9: Procedure of determining the optimal station number and their locations.

To ensure the new facilities will not be an obstruction in the airside, the structure will have a low height and will be covered to ensure safe drone parking. During idle times, drones will be parked here and charged, to be ready whenever called upon. Figure 10 below illustrates the image of the drone station to be built.

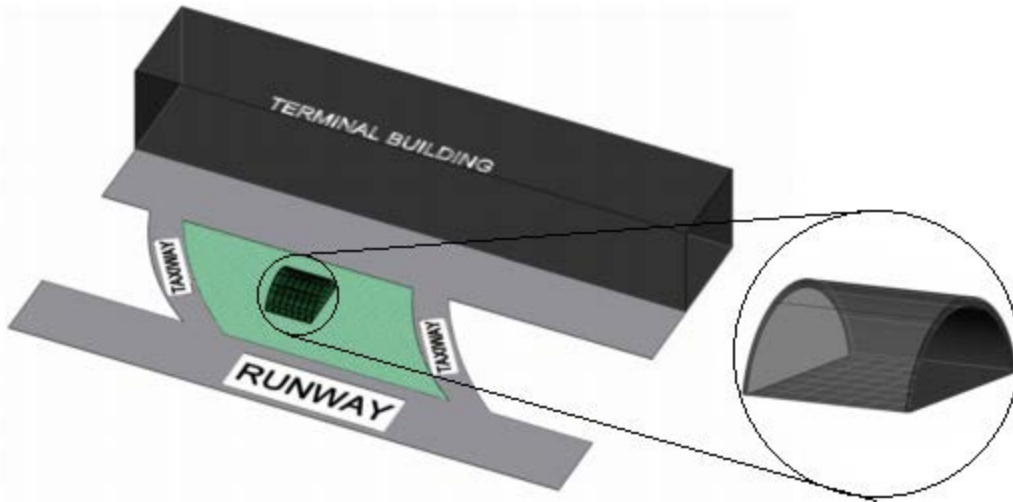


Figure 10: Image of drone station to be placed strategically around the airport (produced on CAD). Not to scale.

The fleet mix at each station will be varied to accommodate pickup of different types of FOD. To remove debris efficiently from the smallest pebble to a well-sized tree branch, small, medium, and large drones should be installed to ensure that the debris can be picked up without failure. Consideration should also be given to the material property of the debris: depending on what the item is, the pickup maneuver should differ. For instance, based on the existing technology discussed, some drones should have an eagle-claw pickup capability, while others should have a quadcopter-enabled vertical pickup ability. To react to various situations, each drone station is recommended to have UASs with differing characteristics.

Furthermore, for the UASs to be visible during flight, the entire fleet should be equipped with a transponder to allow the drone to be tracked precisely by ATC and FOD removal personnel at all times. Mounting special lighting fixtures will be useful for visibility purposes as well.

Like any machinery, the drones should undergo regular and preventative maintenance. Consequently, the airport must create a new division to conduct drone maintenance. On top of the stationed drones, additional drones must be added to the fleet to act as “safety stock.”

4.5 STABILITY CONSIDERATIONS

Although many factors must be evaluated thoroughly, stability is the aspect that should arguably be considered the most. From a control perspective, maintaining drone stability while performing the FOD removal operations is vital for the successful implementation of the idea. Specifically, drones are typically light; if a heavy item (relative to the drone) or unevenly balanced object is picked up, it will be very challenging to maintain stable flight in the return flight. To account for this element, the dispatchment decisions must be accurate with certainty: operators must not send a drone to pick up debris that will be too heavy for the drone to fly safely. Furthermore, the most suitable drone for the job must be selected for dispatch without fail.

LAX indicated that most of the debris found on the airport ground is trash that flew from nearby locations (R. Vitale, personal communication, November 13, 2015). These common litter items are usually light, small, and made of plastic. Since most FOD are known to be light and relatively small, drone technology today such as the eagle claw and quadcopters should be sufficient for accurate and prompt obstruction removal.

5 SAFETY CONSIDERATIONS

Closely referencing the FAA Safety Management Systems Manual, risk management analysis is performed to ensure the drone-enabled FOD removal proposal will comply with FAA standards and be a viable idea.

5.1 IDENTIFYING POTENTIAL HAZARDS

Potential risks associated with the idea are outlined below in Table 2a: five hazards are identified, each assigned severity and likelihood levels from Tables 2b and 2c. Based on these levels, an equivalent level of risk for each potential hazard is determined, which is determined by referring to Figure 11.

Table 2a: List of potential hazards and the corresponding levels of risk.

Potential Hazard	Severity Level	Likelihood Level	Equivalent Level of Risk
Drone cannot pick up the item	Minor	Probable	Medium
Drone drops the item while flying	Minor	Probable	Medium
Drone failure (crash)	Major	Extremely Remote	Medium
Loss of communication between drone and control	Major	Extremely Remote	Medium
Drone mismaneuvers	Major	Extremely Remote	Medium
Terrorism attack (i.e. hacking into drone system)	Catastrophic	Extremely Improbable	Medium/High

Table 2b: Severity Definitions set by FAA. [23]

Catastrophic	Results in multiple fatalities and/or loss of the system
Hazardous	Reduces the capability of the system or the operator ability to cope with adverse conditions to the extent that there would be – Large reduction in safety margin or functional capability; Crew physical distress/excessive workload such that operators cannot be relied upon to perform required tasks accurately or completely; (1) Serious or fatal injury to small number of occupants of aircraft (except operators); Fatal injury to ground personnel and/or general public
Major	Reduces the capability of the system or the operators to cope with adverse operating condition to the extent that there would be – Significant reduction in safety margin or functional capability; Significant increase in operator workload; Conditions impairing operator efficiency or creating significant discomfort; Physical distress to occupants of aircraft (except operator) including injuries; Major occupational illness and/or major environmental damage, and/or major property damage
Minor	Does not significantly reduce system safety. Actions required by operators are well within their capabilities. Include: Slight reduction in safety margin or functional capabilities; Slight increase in workload such as routine flight plan changes; Some physical discomfort to occupants or aircraft (except operators); Minor occupational illness and/or minor environmental damage, and/or minor property damage
No Safety Effect	Has no effect on safety

Table 2c: Likelihood Definitions set by FAA [23].

Probable	Qualitative: Anticipated to occur one or more times during the entire system/operational life of an item. Quantitative: Probability of occurrence per operational hour is greater than 1×10^{-5}
Remote	Qualitative: Unlikely to occur to each item during its total life. May occur several times in the life of an entire system or fleet. Quantitative: Probability of occurrence per operational hour is less than 1×10^{-5} , but greater than 1×10^{-7}
Extremely Remote	Qualitative: Not anticipated to occur to each item during its total life. May occur a few times in the life of an entire system or fleet. Quantitative: Probability of occurrence per operational hour is less than 1×10^{-7} but greater than 1×10^{-9}
Extremely Improbable	Qualitative: So unlikely that it is not anticipated to occur during the entire operational life of an entire system or fleet. Quantitative: Probability of occurrence per operational hour is less than 1×10^{-9}

Severity \ Likelihood	No Safety Effect	Minor	Major	Hazardous	Catastrophic
Frequent	Low Risk	Medium Risk	High Risk	High Risk	High Risk
Probable	Low Risk	Medium Risk	High Risk	High Risk	High Risk
Remote	Low Risk	Low Risk	Medium Risk	High Risk	High Risk
Extremely Remote	Low Risk	Low Risk	Low Risk	Medium Risk	High Risk
Extremely Improbable	Low Risk	Low Risk	Low Risk	Low Risk	Medium Risk



Figure 11: Risk Acceptability Matrix. [24]

The level of risk results determined above may lead to criticism that the system is unsafe. Nonetheless, the FAA defines medium risk as acceptable as long as the risks are closely monitored and mitigated. Moreover, these results are extremely conservative: in reality; many of these risks should not be as high as these worst-case scenarios defined in

our analysis. For instance, improvements in UAS technology will reduce the chances of failed FOD pickup maneuvers, and strict airport security will help prevent undesirable events from

happening. Tactics to cope with the hazards will be discussed in more detail in the following section.

5.2 PREVENTING THE INHERENT RISKS

With the correct measures the risks associated with FOD removal procedures can be prevented or greatly reduced. In the first case where the drone may be unable to pick up the item, this may result in additional risk for leaving the FOD untreated for a longer period of time, and for dispatching a drone unnecessarily, making it prone to other associated risks. When this happens, the FOD removal team must immediately close off the area and dispatch ground vehicles to resolve the issue. To reduce the chances of this happening, making the correct decisions at the drone dispatchment stage is vital.

As discussed in the drone stability section, there is a risk of the debris being dropped during the transport stage. If this happens, the maintenance team and the control tower should be alerted immediately. The responsible personnel shall quickly examine the situation and act accordingly. Possible actions include re-dispatching the drone to pick up the debris again or closing off the area for manual pickup.

Drones are vehicles as well, and they are prone to accidents. The UAS may crash into taxiways, runways, buildings, or aircraft. To reduce the risks as much as possible, drones will be banned from flying too close to infrastructure or near any vehicle or aircraft. If the drone crashes, the FOD removal team should be prepared to perform immediate area closure and cleanup procedures.

As the drones will be “teleoperated,” communications between the drone and the navigators might be lost. If the drone maintains its altitude rather than merely crashing, it may be difficult to resolve the issue. A suggestion is to use an “interceptor drone” (Figure 12).

Introduced to the Tokyo Police Department late last year, these drones are designed to chase suspicious-looking drones and capture them using large nets. In addition, these drones can also be used to contain private drones flying too close to restricted airport areas.



Figure 12: An interceptor drone catching a smaller drone in its net. [25]

Because of human intervention in the proposed system, security concerns with flying drones in restricted areas must be seriously considered. In addition to a thorough and specialized training program for the pilots, a system ensuring joint accountability for all operators must be established. To reduce

navigation errors, operators must be aware that any mistake would cause detrimental impacts to the system's credibility. On a related note, the drone system may be subject to terrorism attacks. To prevent this, the system must have high security measures to avoid any unauthorized access.

6 INTERACTION WITH INDUSTRY EXPERTS

Throughout the process of exploring the feasibility of the suggested UAS-enabled FOD removal idea, our team sought advice from various experts, including UC Berkeley faculty, airport officials, and industry affiliates. Based on the communications, we were able to gauge the real-life impacts of our idea and improve the proposal by incorporating expert opinions.

At UC Berkeley we interacted with Professor Raja Sengupta of the Civil and Environmental Engineering Department, and David Dominguez Hooper, president of the "UAVs @ Berkeley" on-campus group. They have given us valuable advice on the control aspect of

operating drones. We were able to elaborate on the concept of “teleoperation” of drones from a remote location. We also discussed stability issues of drone flights in detail.

The team also obtained industry opinions from five experts in the field. Oakland International Airport (OAK)’s Operations Superintendent, Darron Evans, recognizes the idea as having the capability to meet the needs for reducing the impacts of FOD, but simultaneously admits to the challenges of the proposal because of the operational complexities. Specifically, Evans mentioned the difficulty of coordinating drone operations across ATC personnel and ground maintenance staff. Tom Bock, Manager of Operations at Newark Liberty International Airport (EWR), expressed concerns whether or not the FAA will be open to lifting the ban on drone operations at or near airports in the near future. Tom Cornell, Director of Aviation Planning at Landrum & Brown, also advised us that endurance considerations and operational approvals of drones must be addressed in the plan. Taking these critiques into consideration, our team has updated the design description so that these issues are addressed.

Nonetheless, almost all of the experts expressed an overall positive feedback on the idea’s concept. For instance, Brad Bachtel, former Manager of Airport Compatibility of Boeing, believes in the idea’s effectiveness and feasibility. From a safety standpoint, Bachtel shared an anecdote of when he worked at Houston Hobby Airport:

[From] 1980--1983, I worked at Hobby Airport (HOU) and twice during that time the tower forgot I was on the runway doing the inspections. Seeing a 737 engine in my side rear view mirror was unsettling to say the least and both times I was able to swerve and head for the infield. In time, drones could be used to do more of the runway inspections as well (B. Bachtel, personal communication, April 19, 2016).

This first-hand experience reinforces our belief that safety can be improved by implementing the FOD removal idea.

Captain Frank Ketcham, a commercial pilot and aviation specialist, also shared his insight from a pilot's perspective. He believes that airports are actually very good environments to implement drones, and the proposed system can be very valuable for maintaining safety. Ketcham mentions that pilots would benefit from real-time reports of runway conditions: scanning the runways on periodic surveillance trips could



Figure 13: Group photo of UC Berkeley students at the LAX on-site tour, 2015.

be a secondary task performed by the FOD removal drones. Through the interview, the team also gained perspective into additional tasks for the UASs.

Last fall, our team had the opportunity to tour the Los Angeles International Airport (LAX), and we interacted with Los Angeles World Airports (LAWA) officials regarding the frequency of FOD instances at LAX and the procedures to resolve the issue (Figure 13). The on-site tour allowed us to envision how the system will be implemented more clearly.

7 BENEFITS OF DESIGN

Possible benefits of the FOD removal proposal include increased safety, reduced financial risk, and increased capacity. Cost-benefit analyses support our proposal and its commercial viability.

7.1 INCREASED SAFETY

Today, even with the most up-to-date technology in airports, personnel are still expected to risk being on the runway to perform sweeping, monitoring, and removing FOD. Working around aircraft, using taxiways and driving personnel to runways for removal is dangerous regardless of training and expertise of workers. Implementing the drone system will significantly

decrease the human physical participation. Drones can be used to remove FOD in a shorter time and sent out without the concern of putting lives in danger.

Also, by installing this drone system and allowing an improved detection and removal procedure of the debris, the overall safety of passengers and airport staff can be improved; the possibility of FOD-related accidents occurring will be reduced significantly.

As previously mentioned, one of the key scenarios for the drone removal to be used for is when high-speed debris pickup is required. In the case where debris occurs while an aircraft is approaching the runway, the swift pickup maneuvers performed by the drones will allow for a continuous flow of safe landings, especially when it is too late for a descending aircraft to abort its planned landing.

Airports are considered to be the safest transportation facilities to exist. By integrating this drone system we will be significantly reducing future FOD incidents.

7.2 REDUCED FINANCIAL RISK

Historical evidence shows the hazardous and financially strenuous effects of FOD. Debris on runways is easily sucked into engines, which can potentially cause a great danger to the passengers and/or substantial damage to the aircraft itself. For example, “a single blade inside a jet engine on a Boeing 777 costs about \$40,000” [26]. Not only is this cost a major financial burden for the airlines, but such incidents will also have an extreme impact on the airline's reputation. A tragic incident that involves deaths will limit the expansion and growing profit of the airline for years to come.

FOD incidents should be avoided at all costs. Luckily, drone technology is surprisingly not all that expensive, and it is expected to become cheaper in the near future as these products become mass-produced worldwide.

7.3 INCREASED CAPACITY

Utilizing the drone removal procedure in *ad hoc* situations will most surely increase capacity. An in-depth case study will be reviewed to evaluate the financial implications of incorporating the proposed system in the following section.

7.4 COST-BENEFIT ANALYSIS

BOS airport was selected as the site to study. As the busiest hub in the New England region, BOS ranks 20th in the nation in passenger volume and 19th in flight movements [27].

Notably, BOS Airport already has the XSight's FODetect sensor detection system in place. The proposed idea is dependent on the combination of debris detection technologies and innovative removal maneuvers. The effective integration with already existing technology will most surely lower the hurdle for implementing a drone system—from a technological and a



Figure 14: Location of 9/27 Runway at BOS and proposed station location [28].

financial standpoint. The expected impacts and the existence of a foundation to build upon make BOS an attractive site for case study purposes.

Reasonable assumptions were made in conducting the analysis. First, the drone system will be installed only on the 9/27 runway (where the FODetect sensors are in place). As the concept of drones performing tasks at airports has not been introduced anywhere yet, working in incremental steps will be optimal in the process. The 9/27 runway will be a good starting point

for the idea. Secondly, the “drone station,” where the debris removal UASs will be dispatched from, will be located at the midpoint of the runway, as shown in Figure 14. This placement will allow for equidistant access to all areas of the runway. For simplicity, economic benefits gained by airports will be calculated from landing fees. Although this entity does not capture all of the potential benefits, it is a good measure that is easily quantifiable.

Table 3 includes essential data for conducting the case study. As the busiest airport in New England, BOS handles over 30 million passengers and over 300,000 passenger operations annually. To simplify the calculations, it is assumed that each passenger operation carries approximately 100 passengers. In conducting further calculations, all aircraft are assumed to be Boeing 737-300s, a mid-sized aircraft fitting the conditions computed below. As aircraft range from small regional jets to the massive A380s, the assumption seems to be a valid choice, as it has an aircraft weight close to the median of all aircraft operated at BOS.

Table 3: Passenger data at Boston Logan International Airport and capacity of B737-300. [29]

Total Passengers in 2014	31,634,445
Total Passenger Operations in 2014	331,672
Average Number of Passengers per Flight	96
B737-300 Capacity	108-146 passengers

Further data necessary for computation is given as follows, in Table 4. Importantly, the landing fees, which make up 25% of operating revenue at large airports, is set at \$4.34 per 1,000 pounds at BOS. The speed of the drone is taken from the specifications of the MD4-1000 model discussed earlier. The velocity of 49 feet per second corresponds to approximately 33 MPH, depicting the swiftness of the UAS.

Table 4: Further data at Boston Logan International Airport. [30]

B737-300 Maximum Landing Weight	114,000 lbs.
Landing Fees	\$4.34 per 1,000 lbs.
Landing Cost per Aircraft	\$495 per landing
Runway 9/27 Length	7,001 feet
Speed of Drone	49 ft./sec.

In determining the final figures, several calculations were performed. According to Massport [31], there were 3,720 landings in October 2015 on the 9/27 runway. This value corresponds to approximately 0.083 operations per minute. Furthermore, the average time required for a drone to be dispatched, remove the debris, and return to base will be calculated by:

$$\frac{\text{Average Distance Traveled}}{\text{UAV Speed}} = \frac{7001\text{ft}}{2} \times \frac{1}{49\text{ft/sec}} = 1.19\text{ min.}$$

The standard FOD removal time is estimated to be roughly 10 minutes [20]. By replacing the current pick up procedure with the drone-enabled operations, we obtain:

$$\text{Saved time per drone operation} = 10 - 1.19 = 8.81\text{ min.}$$

Since 0.083 operations per minute is the rate on the runway, and each landing earns \$495 in fees, the financial gain is computed as follows.

$$\begin{aligned} \text{Equivalent \$ Saved} &= \frac{0.083\text{ operations}}{\text{min}} \times 8.81\text{ min} \times \frac{\$495}{\text{operation}} \\ &= \$362\text{ per operation} \end{aligned}$$

At European airports, where FOD-related instances are tracked, it is reported that approximately 200-240 minutes of runway closure is performed as a result of FOD every month [32]. Still assuming the 10 minute closure time, this corresponds to 20-24 instances of runway

FOD occurrences each month. A 50% drone dispatch rate (assumption) is equivalent to 10 operations per month; this leads to an annual savings of \$43,440 for the airport.

Considering the direct benefits, one can judge that a 2-3 year time span will pay off the initial capital investment of purchasing the drones (priced at \$30,000 each for a MD4-1000). One must consider other costs as well, such as other capital costs (building the station infrastructure), maintenance, operating, and labor. Insufficient information makes estimating these exact costs difficult; however, what is known is the additional costs in hiring drone navigators. If three additional positions (PIC, VO, and manager) must be filled for 14 hours a day and 365 days a year, 15,330 additional man-hours are required. By no means is this cheap: assuming an hourly wage of \$50, the labor cost needed is \$766,500 annually. Factoring in the other fixed costs, it can be inferred that the system will cost on the magnitude of \$1 million to \$2 million per year to operate.

From a financial standpoint, the \$43,400 annual benefit discussed earlier alone will not justify implementing the system. The Insight SRI study, however, shows that the direct cost of FOD can be quantified to \$0.13 per passenger [32]. As BOS handled almost 32 million passengers in 2014, the equivalent direct cost from FOD can be quantified as over \$4 million. Assuming the drone dispatch rate to be 50%, the potential savings will amount to \$2 million. Although further analysis will be required going forward, the robust calculations above support the argument that the new UAS-enabled system is not an outrageous proposal; rather, it can be a promising financial investment.

7.5 COMMERCIAL VIABILITY

Implementation costs may be a burden for airports looking into such a system. Indeed, purchasing drones, constructing drone stations, hiring additional employees, and maintenance

costs may be significant. FAA grants are available when installing new systems enhancing airport safety. As with BOS's Xsight FODetect system, the FAA financed over 50% of the costs when installing the system. Also, there is an optimistic perspective that as drones become more ubiquitous and technology improves rapidly, related costs will be greatly reduced over time.

To maximize the utility gained from such an idea, selecting an appropriate site to introduce the anti-FOD drones is important. Ideally, a relatively busy airport with mild weather conditions would be optimal for drones to be utilized efficiently. Choosing an airport with an already existing advanced radar system will also be vital in cutting implementation time and costs.

Although thorough analysis has been conducted, a gray zone remains regarding how limited UAS activity should be in restricted airspace, such as airports. Current FAA regulations forbid private UAS operations within 5 nautical miles of an airport. In parallel with the proposal, the FAA and applicable parties should closely examine related restrictions and agree upon unified ground rules to set UAS operating rules.

As airports are greatly concerned with safety, many officials may have conservative attitudes in considering new systems, especially involving drones. For the proposal to be implemented smoothly, OAK recommends a two-phase rollout plan. In the first phase, the product will be introduced as a FOD locator, and airport staff will remove the occurrence in all cases (D.Evans, personal communication, April 21, 2016). Once this first step becomes refined, the second phase will be initialized, which will involve the actual drone pickup of FOD. Like the suggestion, incremental steps will be valuable in getting all players on board with the idea and in displaying the benefits that the system will bring.

8 CONCLUSIONS

Implementing a drone system into an already existing framework is what makes people skeptical of the widespread usage of UASs. FOD, at a minimum, is a common source of flight delays and a logistic annoyance. When dangerous FOD go undetected, however, the consequences can be catastrophic. Through our research of drone capabilities and its applications to debris removal, we strongly believe that drones are an effective supplement to current methods of FOD removal.

Understanding that although many hurdles exist to implement drone-enabled systems at airports, doing so may very well provide innovative solutions that will enhance operational efficiency and safety and reduce financial risks. Future studies will allow for further acceptance of UAS applications in the aviation community.

APPENDIX A - CONTACT INFORMATION

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APPENDIX B - DESCRIPTION OF THE UNIVERSITY

University of California, Berkeley is the world's number one public university in the Academic Ranking of World Universities for 2016. It serves as a home for higher education for 36,000 students, including 25,700 undergraduates and 10,300 graduate students. UC Berkeley holds 1,455 permanent faculty and 7,059 permanent staff serving among 14 colleges and schools with 130 academic departments and more than 100 research units. More than half of all UC Berkeley seniors have assisted faculty with research or creative projects and more UC Berkeley undergraduates go on to earn Ph.D.s than any other U.S. university.

The Civil and Environmental Engineering department consistently ranks at the top of the best civil engineering programs in the country by *U.S. News and World Report*. The Department of Civil and Environmental Engineering has 50 full-time faculty members and twenty-two staff dedicated to the education of more than 400 undergraduate students and 360 graduate students. The education in the department prepares students for leadership in the profession of civil and environmental engineering and sends approximately one-quarter of its undergraduates into a graduate education. Our CEE laboratories for teaching and research are among the best in the nation, providing opportunities for hands-on experience for all students. There is no other location with comparable resources in the San Francisco Bay Area that can provide students with ground-breaking local civil and environmental engineering projects and participate in professional activities.

UC Berkeley was chartered in 1868 as the first University of California in the multi-campus UC system. The school houses a library system that contains more than 10 million volumes and is among the top five research libraries in North America. Throughout its full history, Berkeley has had 21 Nobel Laureates, 234 American Academy of Arts and Sciences Fellows, 213 American Association for the Advancement of Science Fellows, 363 Guggenheim Fellows, 32 MacArthur "genius" Fellows and four Pulitzer Prize winners. Just as important as academic excellence, UC Berkeley has held a respectable active history of public service. More than 7,000 UC Berkeley students every year do volunteer work in 240 service-oriented programs while there are more Peace Corps volunteers from UC Berkeley than from any other university. Clearly, UC Berkeley is not solely focused on academia as countless research and outreach initiatives focus on public benefits to the community, nation, and world.

APPENDIX C - NON-UNIVERSITY PARTNERS

N/A

APPENDIX E - EVALUATION OF EDUCATIONAL EXPERIENCE

Students

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?

The ACRP University Design Competition for Addressing Airports Needs has been a worthwhile experience for all of us. It was very stimulating to use the knowledge we learned from class in formulating a real-life solution to address current needs in the aviation field. This was the first full-scale design project that most of us had undertaken, so this competition was a good way to gain experience in completing a large-scale project. Furthermore, as all of the team members have different engineering interests (from Environmental Engineering to Transportation and Industrial Engineering), it was very fun collaborating and sharing new ideas among one another. I hope this experience will be useful in our future academic and industry endeavors.

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

Selecting our topic and formulating the design was a big challenge our team faced. Our team wanted to come up with an innovative model that has not been addressed before, but during the brainstorming process, we discovered through research that many of our proposed ideas were already taken. Therefore, we decided to think outside the box, and combine ideas from an up and coming hot field (UAVs) with safety aspects (which can always be improved). Another challenge we met was lack of data for the case study. Since our case study requires a large amount of FOD occurrence data, we reached out to professionals in aviation field and Professor Rakas also contributed significantly in this process.

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

After literature review, our team understood that FOD is a significant issue that airport officials must deal with, and that much of the removal process is quite analog. Recent proposals have suggested the implementation of fully automated systems; these ideas are interesting, but we felt that they fail to account for the fact that converting the FOD removal process to an entirely automated one is a radical change that may be faced with strong opposition. Therefore, we decided to develop our hypothesis so that it would be incremental and not fully automated.

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

Participation by industry in the project has been highly meaningful and useful in all aspects. Fortunately, the professionals we reached out to provided us with lots of valuable feedback. The opinions and advices provided by the experts allowed us to refine our model throughout the writing process. In addition, participation by industry also provided credibility to our project and added confidence to our team. We appreciate all of their help in completing this project.

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?

The competition enables us to develop a better understanding of overall structure of a group research project. We are positive that all of us (whether pursuing graduate studies or entering the industry) will put many of the experience we gained from this into practice. All of us also had fun while doing research since we were finally able to use our own creativity, knowledge and experience to “sell” our own innovative idea.

Faculty

1. Describe the value of the educational experience for your student(s) participating in this Competition submission.

My students gained tremendous educational value from this Competition. They went through the entire creative process of designing a system for FOD removal at runways with UASs from the initial stages to the end by designing a concept, applying it to a busy airport, and testing its feasibility. As some of the students are planning to attend various graduate programs, this educational experience was an ideal means for them to learn about how to start creating new concepts and new knowledge. Once they start their graduate programs, the experience gained while participating in this Competition submission process will help them make a smoother transition towards conducting more advanced research that is expected in any graduate program.

2. Was the learning experience appropriate to the course level or context in which the competition was undertaken?

The learning experience was quite appropriate for the context in which the competition was undertaken. It tested the intellectual capability of the students at the right level, and offered challenging insight into practical, "real-world" problems. Although the research group was relatively small (4 students), the students cooperated, organized, and designated tasks within a complex goal-oriented endeavor.

3. What challenges did the students face and overcome?

The students faced and successfully overcame many challenges. First, these are undergraduate students with no prior experience in conducting research. Furthermore, they came from a civil engineering and operations research background, and had little previous knowledge or understanding of aviation or airport systems, FOD, and UASs. Many of the student-team members never took any formal aviation classes. The Airport Design class that some of the students took the previous semester was their only formal education in aviation. Hence, the beginning of the research process included a long learning process about how to conduct research and how to understand more advanced aviation concepts, such as the concept of runway operations, runway maintenance, UASs, and safety issues with UASs. Another challenge the students faced was the initial resistance of their proposed concept by airport operators and industry experts, and the industry’s initial "suspicion" about the proposed design. Whenever the experts commented on their design from a more tactical, today’s operational perspective, the students very professionally and patiently would explain their paradigms and strategic goals. Consequently, their communication with the airport operators and industry experts was a very positive and productive enterprise.

4. Would you use this Competition as an educational vehicle in the future? Why or why not?

I would definitely use this Competition as an educational vehicle in the future. In previous years I conducted a significant amount of undergraduate research through the UC Berkeley Undergraduate Research Opportunities (URO) program. This program was designed to assist undergraduate students in developing research skills early in their college education. On average, half of my students from the Airport Design Class would participate in aviation research projects in the following semester, and would formally be funded and sponsored by URO. Because of recent budget cuts, however, this program had to be closed. By using this Competition as an educational vehicle, I am not only continuing research with undergraduate students, but also teaching them how to structure, organize, and present their work to a large number of experts in the field.

5. Are there changes to the Competition that you would suggest for future years?

I would expand Challenge Areas by adding more emphasis on the Next Generation Air Transportation System (NextGen) requirements and expectations, as well as on aviation sustainability.

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