FODHippo

An Automated Debris Collection System for Airport Runways

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Airport Operation and Maintenance Challenge

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Executive Summary

The purpose of this report is to present our design for the FODHippo system, a distributed, automated foreign object debris (FOD) removal system for airport runways.

FOD costs the airline industry over 12 billion dollars annually. In addition to causing damage to aircraft, FOD is also a large source of air traffic delays, which are both a large financial drain on airport operators and a nuisance to passengers. In order to reduce the danger due to FOD and the related costs, we decided to develop a distributed, autonomous FOD retrieval system.

By reviewing existing technologies, we established a baseline from which to work from. Xsight Systems, for example, produces stationary sensors capable of detecting FOD on a runway and determining its GPS coordinates. This system increases the ease of FOD detection but still requires a human in the loop. Instead, we envision an autonomous system which could provide faster reaction times in addition to off-peak preventative sweeps.

After meeting with officials at Boston Logan International Airport and consulting FAA Advisory Circulars, we were able to derive a set of specifications for our envisioned system. These specifications both provided a framework for our design process and a metric by which to grade our results.

In executing and implementing our design, we developed two prototypes. The first prototype focused on the FOD retrieval mechanism with an emphasis on enabling the removal of objects the size of dead birds from runways. In contrast, the main focus of the second prototype was GPS waypoint navigation, a requirement for autonomous FOD retrieval. Along with physical prototypes, we addressed several systems level issues such as integrating this type of device into existing airport operations as well as issues of how to effectively display and use data obtained by the device.

One of the major steps required to implement a system like this at an airport is the safety risk management (SRM) process. We first identified a number of hazards and then used FAA guidelines to quantitatively examine the risks inherent in each. We also formulated ways to mitigate these risks; namely, defining an “abort” protocol and GPS boundaries.

Communications with industry experts were critical to the design process and provided an invaluable source of feedback; a description of industry interactions is also included in the report.

Additionally, we evaluated the projected impact of our design. This takes the form of a cost/benefit analysis in which we roughly calculated the cost of installing the proposed system in an airport as well as the savings created by the system. We found that the $2M system pays for itself after approximately one year from reductions in engine ingestion related damage ($1.6M) and costs associated with delays ($700K).

The two prototypes collectively demonstrate much of the locomotion, communication, FOD removal, FOD storage, and navigation functionalities required of the final product. Along with the proposed additions, improvements, and operational strategies, we are confident that the overall system will be able to provide both an increase in safety and a decrease in delays, resulting in an annual savings of roughly $2.3 million for a large airport.

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List of Definitions

Acme	A trapezoidal screw thread profile.
Arduino	An open-source low-cost single-board microcontroller.
Autonomous	Acting independently or having the freedom to do so.
Incursion	Any unauthorized intrusion onto a runway, regardless of whether or not the aircraft presents a potential conflict.
Massport	The port authority in the Commonwealth of Massachusetts that owns and operates Boston Logan International Airport as well as several other transportation facilities.
Odometry	The use of motor encoders to determine a robot's change in position and orientation relative to some previous position.
SolidWorks	A 3D computer aided design program.
Tetrix	A design system for construction using aluminum elements created by Pitsco.
Timing belt	A rubber belt with teeth used to transmit torque.
Leadscrew	A screw designed to translate rotational motion into linear motion.
Waypoint navigation	The process or activity of accurately ascertaining one's position and planning and following a route using reference points in physical space.

List of Abbreviations, Acronyms, and Initialisms

ADS-B	A NextGen surveillance technology for tracking aircraft
FAA	Federal Aviation Administration
FOD	Foreign Object Debris
GPS	Global Positioning System
SRM	Safety Risk Management

Background and Problem Statement

Foreign object debris, or FOD, is a major safety issue at airports. A variety of objects frequently find their way onto airport runways where they can be ingested into jet engines or otherwise cause serious damage to aircraft. This resulting damage to the engine, body, or landing gear of an aircraft can lead to passenger injuries or even fatalities. The most common sources of debris are various tools, which can be misplaced by mechanics, and dead birds, which can get caught up in planes' wakes. Objects range in size from as small as nuts and bolts to as large as a suitcase. In fact, FOD costs the airline industry over 12 billion dollars every year. [1]

While damage caused by FOD, either via engine ingestion or collision with the aircraft, amounts to a significant portion of this total (in parts, labor, and other repair costs), there are many indirect costs as well. One of the most expensive byproducts of FOD is the cost of delays; when FOD damage occurs, it not only delays the damaged plane, but also slows down all flights scheduled to take off or land on that runway (and potentially others, as well). In addition to the time required for the plane to exit the runway, the need to perform repairs, testing, and possibly change planes quickly adds up to a large decrease in efficiency. In 2000, a piece of FOD that went unnoticed on the runway at Charles de Gaulle International Airport resulted in the crash of an Air France Concorde, resulting in the deaths of 113 people. [2] To avoid similar tragedies, airport personnel must shut down the runway and mobilize to remove FOD as soon as it is found, thereby further contributing to delays.

In order to prevent aircraft damage and maintain safety and efficiency, runways must be kept free of FOD while aircraft are operating. To accomplish this, they are checked regularly by airport personnel and are also monitored by pilots who check the runways as they take off and land. Many airports have also begun to implement automated detection systems to ensure that no

FOD goes unnoticed. Boston Logan International Airport, for example, is working with Xsight Systems, based in Israel, to install their FODetect system along one of the runways.[1] [3]

In order to remove FOD from a runway, the runway must be shut down, preventing any aircraft from taking off or landing. Only once the runway is entirely clear of traffic can a worker proceed to the location of the FOD and remove it manually. This can be both a time consuming and manpower intensive process. Additionally, any time a person goes out onto the runway there are a number of risks involved, including interrupting traffic on another runway or leaving potential FOD behind.

Our goal is to develop an autonomous FOD removal system, which will ultimately increase the safety of airports and decrease the time commitment and cost required to execute FOD removal procedures. We focused on autonomous removal rather than detection due to the existence of several advanced detection systems currently in development. [3]

Summary of Literature Review

Review of Existing Detection and Removal Systems

As part of the literature review, we studied existing state-of-the-art technologies used for FOD detection and removal. One report, “Performance Assessment of a Mobile, Radar-Based Foreign Object Debris Detection System,” details the performance of the FOD Finder, a mobile FOD detection system used at Chicago O’Hare International Airport. The FOD Finder is a radar-based detection system that can be mounted on a vehicle or truck; it is capable of scanning an 80^{o} area

[1] Logan Airport is used as an example throughout the report both because it’s representative of many high volume airports across the country and because of our opportunity to meet with officials there.

200 m in front of the vehicle while traveling up to and exceeding speeds of 30 mph. The FOD Finder successfully identified 195 of 195 target objects both on and off airport runways while traveling at 15 mph. The target objects in this case were metal cylinders 1 inch tall with a 0.94 inch diameter (as defined in AC 150/5220-24). The system is also capable of determining the location of detected objects using its onboard differential GPS system with an accuracy between 2 and 13 feet. A vacuum can be mounted to the rear of the vehicle to facilitate the removal of any FOD that is detected. In addition to detection and removal, the FOD Finder supports data management and assessment through its FOD reporting system which overlays identified FOD onto a map of the airport after each inspection; this kind of inspection report can be seen in Figure 1 where the red dots represent FOD that has been detected and collected at some point. [4]

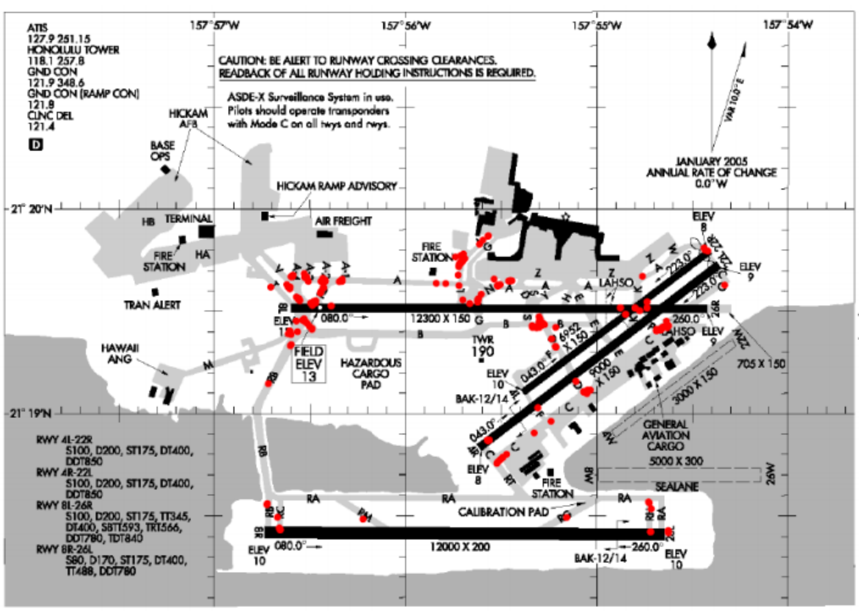

Figure 1: FOD Finder reporting system

There are also stationary systems with similar capabilities, such as Xsight Systems' FODetect and FODspot. These systems are integrated into the existing infrastructure for runway edge lights, requiring little additional infrastructure and placing them in a prime location safely out of harm's way. The system is capable of not only detecting FOD, but also classifying it and determining its exact coordinates. [3]

A large variety of FOD removal technologies currently exist and range from passive collection systems to active sweeping and suction systems. The FOD*BOSS by Aerosweep is a passive debris collection system that uses friction and a series of angled brushes to trap and hold FOD in a mesh sheet as it is dragged over the tarmac. It can be attached to any airport vehicle and can be swept at speeds up to 25 mph. Since it has no moving parts, it is easy to maintain and is relatively reliable and robust. [5]

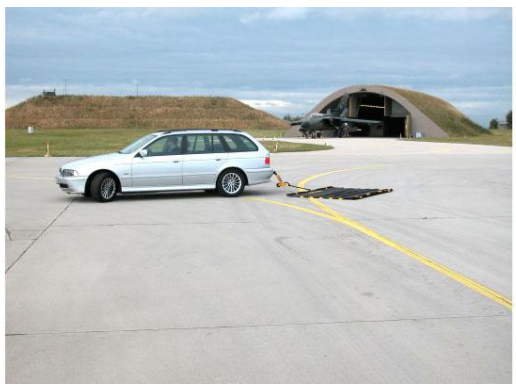

Figure 2: FOD*BOSS by Aerosweep

Literature Review of Airport Operations Documents

FAA Advisory Circulars were invaluable resources in defining specifications for airport operations and for the system as a whole. Four FAA Advisory Circulars were particularly informative: "Airport Safety Self-Inspection" (150/5200-18C), "Airport Foreign Object Debris (FOD) Detection Equipment" (150/5220-24), "Introduction to Safety Management Systems (SMS) for Airport Operators" (150/5200-37), and "Airport Foreign Object Debris (FOD) Management" (150/5210-24). [6] [7] [8] [9]

The “Airport Foreign Object Debris (FOD) Detection Equipment” Advisory Circular serves as a baseline set of specifications for our detection and removal system. The specifications for a mobile radar-based detection system, for example, are that it should scan “an area 600 ft by 600 ft . . . to detect FOD items measuring 1.2 in (3.0 cm) high and 1.5 in (3.8 cm) in diameter . . . [and] operate at speeds of up to 30 mph (50 km/h).” [6] The document also mandates that detection equipment be able to specify the location of detected FOD within 16 feet, which translates to a minimum accuracy for our GPS waypoint navigation system.

In conducting a safety risk assessment of our system both the “Introduction to Safety Management Systems (SMS) for Airport Operators” and “Airport Safety Self-Inspection” served as valuable models of ways to systematically approach the Safety Risk Management (SRM) process. Chapter 3 of the FAA System Safety Handbook also helped in a similar way. In particular, it helped to quantitatively classify the likelihood and qualitatively classify the severity of a given safety risk.

Literature Review of GPS Navigation Techniques

We studied a number of academic papers on the use of GPS localization to aid in the implementation of our navigation system. The papers we reference focus primarily on the fusion of GPS and odometry data to achieve more accurate localization and positioning than the 16 foot resolution of a typical GPS unit. Thrapp et. al. present an implementation of an extended Kalman filter used to aid in the precise positioning of an autonomous campus tour guide at Rice University. Using their approach, the robot is able to remain within 40 centimeters of the desired route. [10] Ohno et. al. used a similar extended Kalman filter method to correct for drift in odometry data and were able to achieve a positioning accuracy of 150 cm over a 240 m path. [11]

Problem Solving Approach

In accordance with its large impact on airport operations, many technologies have been developed to help airport operators detect and remove FOD. However, none of these solutions, be they autonomous FOD detection networks or debris sweeping truck trailers, address the fact that a human is ultimately needed to go out on the runway and retrieve the debris. Consequently, there is potential for an autonomous system to drastically reduce the lag time between FOD detection and removal, thus reducing the annual financial loss from FOD. For this reason, we chose to begin development of a system with these capabilities, which we have named FODHippo.

The project goal is to effectively and efficiently integrate existing detection technologies with our autonomous FOD retrieval system and to do so in a way that maximizes efficiency, minimizes downtime, and reduces safety hazards. To be successful, our system must be capable of working in concert with these existing detection systems, making FOD detection and removal an almost fully automated process. The final system will be distributed in nature, consisting of many individual autonomous robots per airfield. Each robot will be able to receive GPS coordinates of FOD, navigate to that location, locate the object, and remove it without human interaction. As a preventative measure, the system will also be able to search runways and taxiways that aren't in use for foreign objects. The processes involved in executing these two primary capabilities are shown in Figure 3 below.

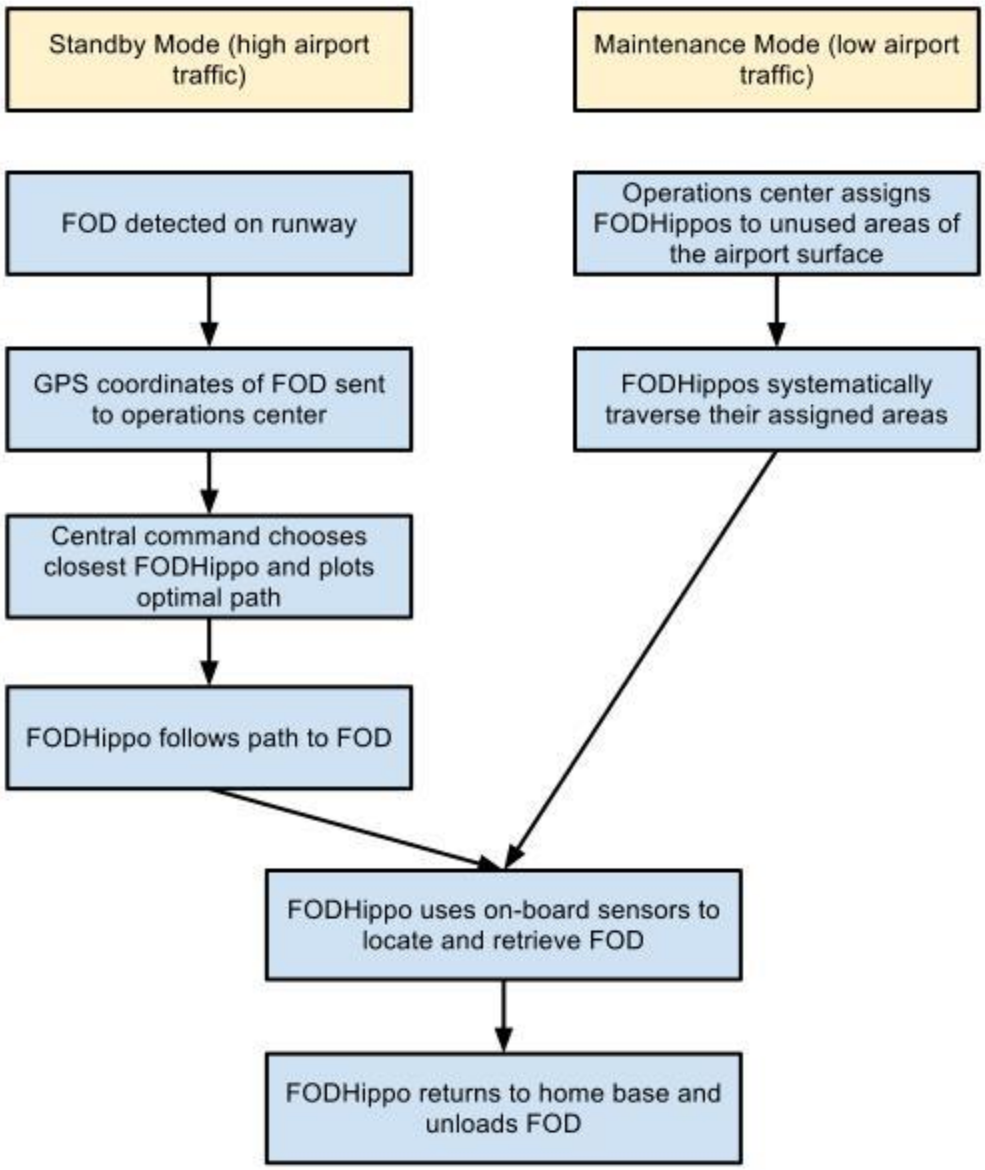

Figure 3: Schematic representation of system operating modes

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During the design and implementation of the FODHippo system, which is named for the ‘Hungry Hippo’ mechanism described in the Technical Aspects section of this report, three factors played a major role in every decision: safety, financial viability, and FAA specifications. In order to ensure that the FODHippo would meet or exceed all consumer and regulatory expectations, we created an extremely detailed set of specifications early in the design process.

Another step we took to simplify the design process was to divide the project into a series of subsystems which could be designed and implemented individually. This allowed for the creation of specifications which only concerned certain portions of the project and prototypes which only tested certain capabilities of the envisioned final device.

In order to develop an appropriate set of specifications it was first necessary to gain a deeper understanding of the needs of airport administrators. To accomplish this, we met several times with Professor Dan Hannon, Robert Lynch, and Flavio Leo. Prof. Hannon is a Professor of the Practice in the Tufts University Department of Mechanical Engineering who works with both the U.S. Department of Transportation and the FAA whereas Mr. Lynch and Mr. Leo both work for Massport and are responsible for administering Boston Logan International Airport.[2] Conversations with these experts, in addition to information gleaned from FAA advisory circulars, led to the development of a collection of customer needs, shown in Table 1.

In order to ensure that the final implementation would meet the industry experts' stated needs, these needs were translated into metrics which could be used to evaluate the performance of a prototype. This mapping is illustrated in Table 1. Next, a set of detailed design specifications was developed by assigning required values and importance levels (1 to 3, with 3 being deemed most important) to all of the metrics, as shown in Table 2.

[2] Further details are available in the Interactions with Airport Operators section below.

Table 1: Mapping customer needs to specifications

	Metrics	Capable of picking up metal and rubber objects	Capable of picking up objects smaller than 3cmx3cm	Minimum FOD removal equipment speed is 15mph	Reliable in a wide range of temperatures	Reliable in a wide range of relative humidity environments	System has a lifespan of 20 years with proper maintenance	Communication Range	Communication Packets Dropped	Wireless protocol complies with FAA Regulations	Pathfinding Accuracy	Ability to remain within boundaries	Largest Dimension	Storage Capacity	Time required to locate/collect FOD once at GPS coordinate	Does not generate FOD	Maximum daily downtime
Customer Needs		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Picks up a variety of objects	1	x	x														
Fast movement speed	2			x													
Robust in weather	3				x	x											
Long lifespan	4						x										
Reliable Wireless Communication	5							x	x	x							
Accurate GPS Position Estimation	6										x						
Pathfinding within boundaries	7										x	x					
Efficient collection/removal	8														x		
Safe vehicle storage area	9												x				
Can collect FOD in bins	10													x			
Minimal Downtime	11																x
Cannot be a source of FOD	12															x	

Table 2: Design specifications

Metrics	Units	Importance	Target
Capable of picking up metal and rubber objects	Pass/Fail	3	Pass
Capable of picking up objects smaller than 3cmx3cm	Pass/Fail	3	Pass
Minimum Transit Speed	MPH	1	15
Operating Temperature	Degrees F	2	32 - 123
Operating Humidity	% Relative	2	5 - 90
System Lifetime	Years	2	20
Communication Range	Miles	3	5
Communication Packets Dropped	Percent	2	1
Wireless protocol complies with FAA Regulations	Pass/Fail	3	Pass
Pathfinding Accuracy	Feet	2	16
Ability to remain within boundaries	Pass/Fail	3	Pass
Largest Dimension	Feet	1	TBD
Storage Capacity	Cubic Feet	2	> 40
Time required to locate/collect FOD once at GPS coordinate	Seconds	3	< 120
Does not generate FOD	Pass/Fail	3	Pass
Maximum daily downtime	Hours	1	< 2

Once we successfully formulated the project specifications, we divided the overall project into subsystems to allow for modular implementation and testing. We split the system into seven components: (1) locomotion, responsible for moving the robot, (2) control/electrical, responsible for communication and coordination of other systems, (3) navigation, responsible for path planning and positioning, (4) detection, responsible for identification and precise localization of FOD, (5) collection, responsible for removing debris from the airport surface, (6) interface, responsible for facilitating human control and monitoring of the device, and (7) base station, responsible for charging the robot and housing both the robot and collected FOD.

Technical Aspects of the Design

We decided to build a first prototype that focused on the implementation of the locomotion, control and collection subsystems, which were seen as the most task-critical. We chose a relatively small (two feet by two feet square) size scale for the first robot for several reasons. The first was cost and ease of fabrication; because we could accomplish a proof-of-concept implementation of the targeted subsystems at this scale we opted not to build a more expensive larger scale prototype. Another concern was safety; if the prototype had been close to the size of the envisioned final product (approximately 5 feet long) any loss of control during testing could have had dangerous consequences. After the first prototype was built and tested, a second prototype of similar scale was fabricated, this time focusing on the navigation subsystem. Looking forward, we envision a future prototype which combines the capabilities of the first two robots and implements a detection subsystem. This future prototype will also have a weatherproof and more robust mechanical design with scaled up dimensions. The design will include a separate base station housing where the robot will return to recharge and unload FOD during inactive periods.

While the design, manufacturing, and testing of the robots themselves were our main focus, a significant effort was made to solve relevant problems on both the systems and operations levels. This has resulted in a detailed outline of how we believe the final product should be operated as well as a summary of the various benefits the device would bring to airports. In addition, a detailed cost analysis was performed to demonstrate the financial viability of the project.

First Prototype

Mechanical Design of First Prototype

Our first prototype implemented a retrieval mechanism, a locomotion system, and wireless control. A full design was drawn up in SolidWorks before we machined the prototype from stock parts in the Tufts Mechanical Engineering Department's Bray machine shop. This prototype removes FOD from the runway with a mechanism used to ingest objects. Due to the motion of the retrieval process, we have given the name "Hungry Hippo" to the mechanism, which is described in more detail below. Additionally, the robot can lower its front ramp using a servo motor to bridge the gap between the ground and the floor of the device. With the ramp lowered, the Hungry Hippo mechanism can be deployed to collect the FOD. This process is controlled remotely; it is further illustrated in a series of photos in Appendix H.

The frame of the robot was fabricated using aluminum plates and U-channels while the floor of the robot and the majority of the Hungry Hippo mechanism is composed of acrylic. The Acme leadscrews and matching threaded blocks used to provide linear translation of the mechanism are made of steel and aluminum, respectively. The complete assembly is pictured in Figure 4.

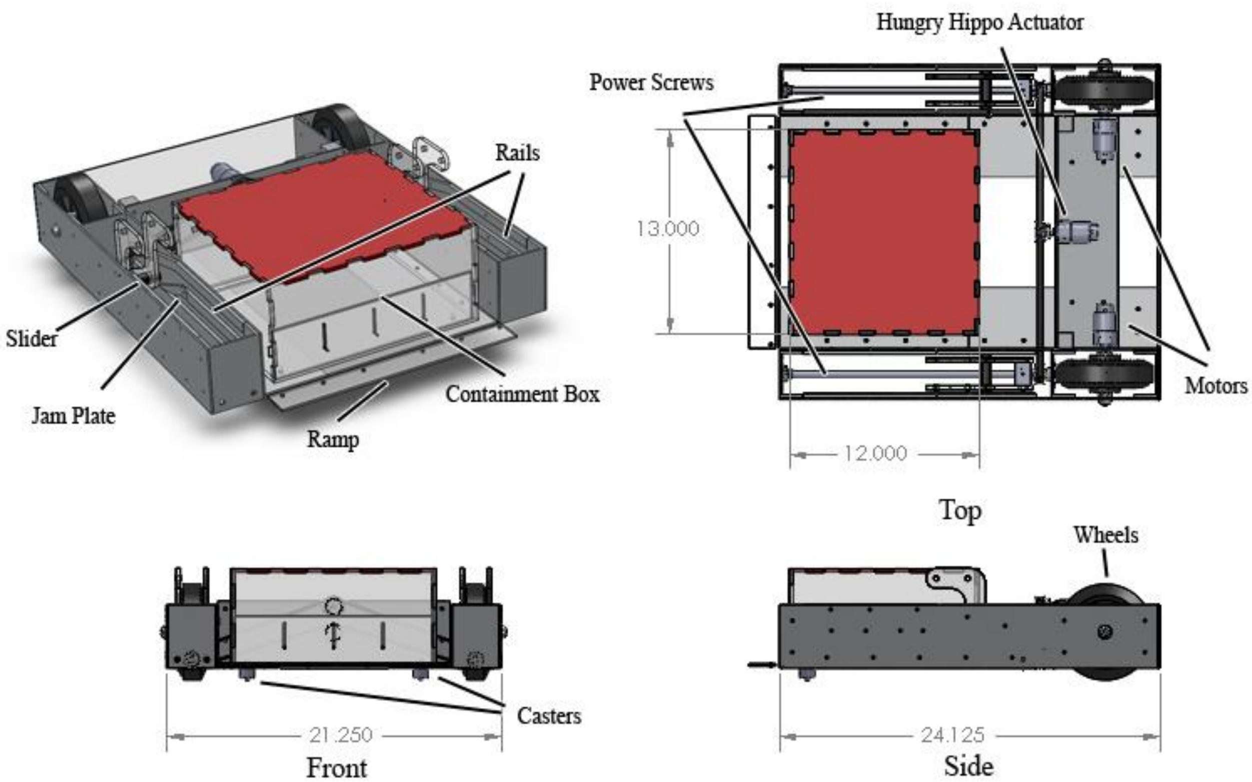


Figure 4: Multi-view drawing of first prototype (all dimensions in inches)

The components which make up this prototype were machined by referencing detailed drawings generated by a comprehensive SolidWorks model, which was also used as a construction guide. As evidenced by Figure 5, the final device is essentially identical to the model. More detailed drawings for the first prototype can be found in Appendix J. The list of parts is in Appendix K.

Figure 5: Comparison between SolidWorks model and actual prototype

Hungry Hippo Mechanism Implementation in First Prototype

The mechanism has one degree of freedom and is designed to capture large sized FOD by actuating an acrylic box to encapsulate the target object and bring it back into the chassis. This motion is accomplished with the use of one actuator: a motor attached to a timing belt. This belt drives two Acme leadscrews which push the box’s supports along rails. The geometry of these rails, which incorporate a hinge, defines the motion of the box, as shown in Figure 6.

The pulley system was chosen to utilize a 350 tooth, 9 millimeter wide timing belt to transmit torque from the motor shaft positioned in the center of the chassis to the two leadscrews in the side channels, as shown in Figure 7. A 1:1 gear-ratio ensures that the 300 ounce·inch (stall) of torque generated by the motor is delivered to the leadscrews at close to the nominal shaft speed of 154 revolutions per minute. Given the specifications of our chosen motor, it was important to choose the proper leadscrews to turn rotational speed/torque into linear motion. An Acme leadscrew with 5-starts was chosen to allow 1 inch of travel per revolution of the shaft. This allowed the mechanism to travel its full stroke of 34 inches in under 15 seconds.

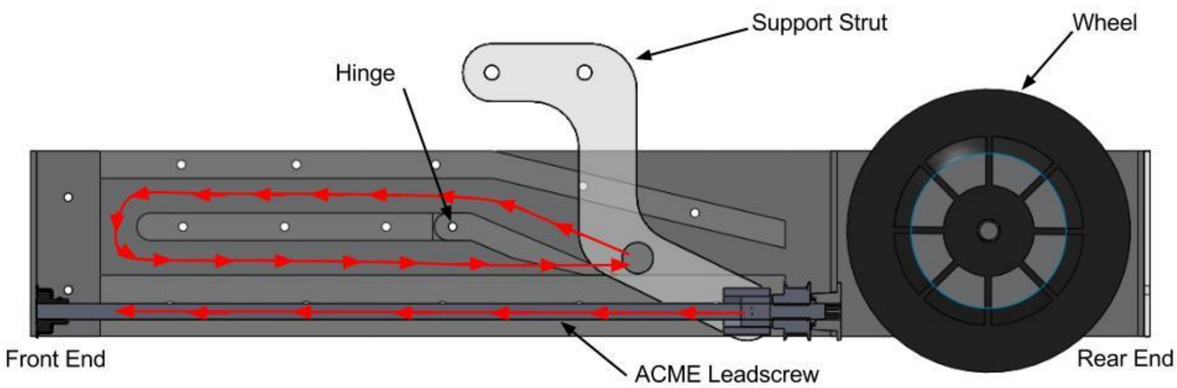


Figure 6: Side view cross section showing path of support strut

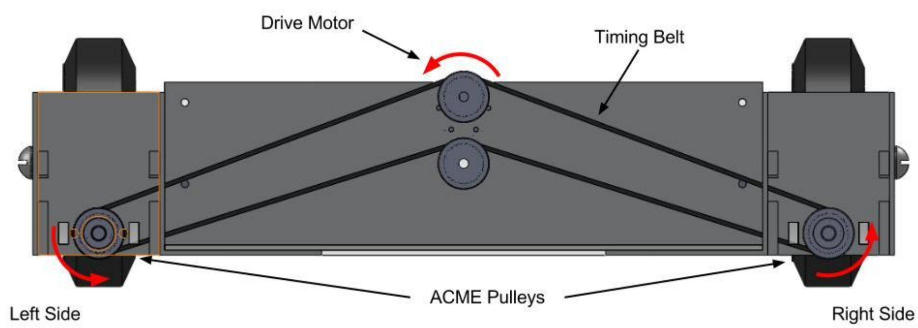


Figure 7: Front view cross section showing pulley system

Electronics Implementation in First Prototype

The electronics used to control the various actuators onboard the robot were also key to the success of the prototype. An Arduino microcontroller was responsible for translating user commands into control signals and operating the actuators using a pair of motor drivers, a Pololu MD03A and a Sparkfun DEV-09213. We selected these motor drivers based upon the stall current of connected actuators; the Pololu device was responsible for controlling the relatively high current Pololu motors that drive the wheels while the Sparkfun device was responsible for control of the lower current Hungry Hippo actuator. The onboard electronics communicate with the operator using a Pololu Wixel wireless device. The system is mapped out in Figure 8 below.

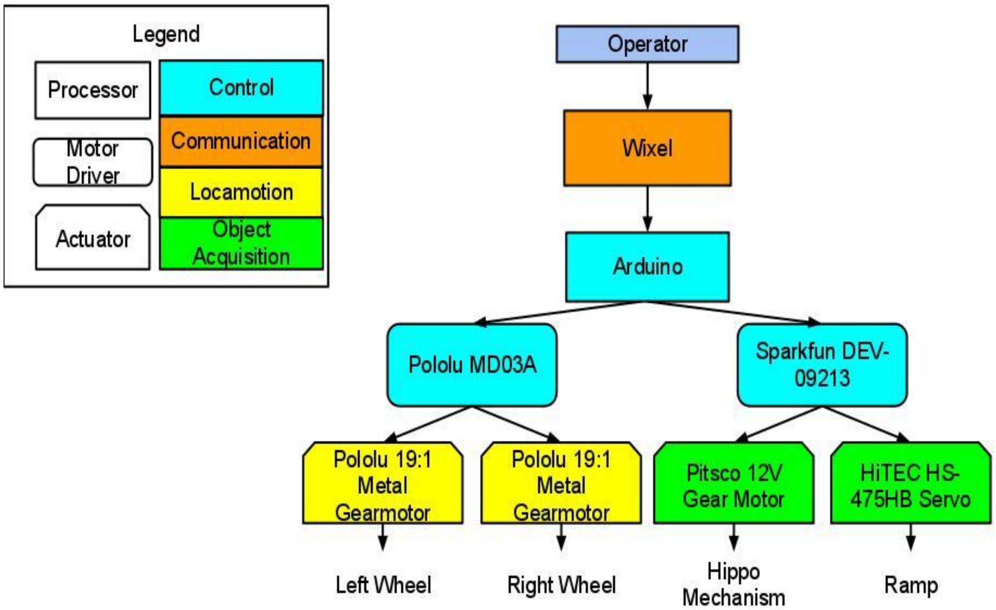


Figure 8: Schematic representation of electronics subsystem

Second Prototype

Mechanical Design of Second Prototype

The second prototype was constructed as a demonstration of the navigation capabilities. The body was primarily constructed from Pitsco Tetrix structural members, using the same wheels and motors as the original prototype. This lighter chassis enabled the team to focus directly on the issue of autonomous navigation with a faster robot by leaving out the capture mechanism. This second prototype can be seen pictured below in Figure 9.

Figure 9: Two views of the second prototype

To guide the robot to an already located piece of FOD, a set of waypoints can be chosen that both direct the robot to its ultimate location and keep it from wandering to parts of the airport that are off-limits, such as active runways and taxiways. The team selected an EM-406A GPS module to provide the robot with a means for self-localization. Using a combination of GPS readings and motor encoders, the robot can navigate from waypoint to waypoint.

GPS Navigation with Second Prototype

In order to allow the robot to navigate autonomously using GPS, a simple and effective control system was devised based upon path linearization and proportional heading control. In the final implementation, the location of FOD will be provided to the device in the form of a GPS coordinate. A map of the airport annotated with the locations of taxiways, runways, and other important landmarks will then be used to plot a safe and efficient path to the debris. This path will then be discretized by splitting it into a collection of waypoints. Therefore, in order to follow the prescribed path, the robot must simply remain pointed towards the next waypoint. A control law, summarized in Figure 10, was designed to accomplish this task.

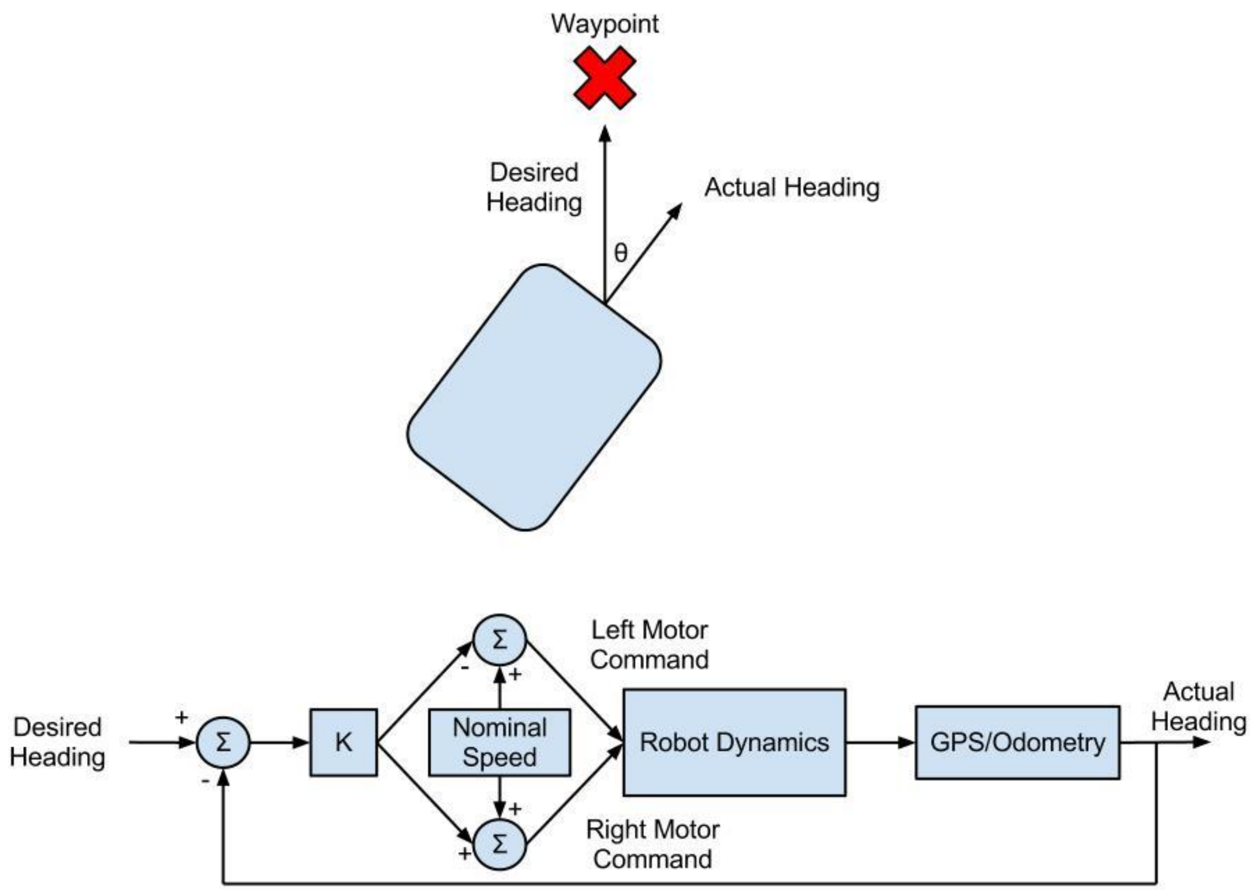


Figure 10: Proportional heading controller

The controller used in Figure 10 varies the power supplied to the left and right motors in response to measurements taken by the GPS sensor and wheel encoders. The reliability and accuracy of the heading provided by the GPS sensor led to its selection as the primary source of direction information, but its slow update rate of approximately 1 Hz precluded it from serving as the sole source of controller input. Wheel encoders were used to allow for heading estimation in between GPS updates. The control loop begins with the device using the FODHippo's current GPS location as well as the provided FOD location to calculate the desired heading. The actual heading is then subtracted off the desired heading to determine the current error, which is multiplied by a control gain, K. The resulting value is then subtracted from the power sent to one motor and added to the other, resulting in rotation in the opposite direction of the error with no change in the vehicle's speed. The complete navigational algorithm is illustrated schematically in Figure 11.

The final version of the system would also include an additional fail-safe GPS system capable of shutting down the entire robot that will operate on a separate communication line and from its own power. This system would be similar to ADS-B (the FAA's NextGen "Automatic Dependent Surveillance-Broadcast" system currently being installed in aircraft) in that it would broadcast the robot's position, velocity, and identification information. [12] This would allow for the system's operator (or some central computer) to shut down the robot if its primary GPS malfunctions and it strays from its intended path.

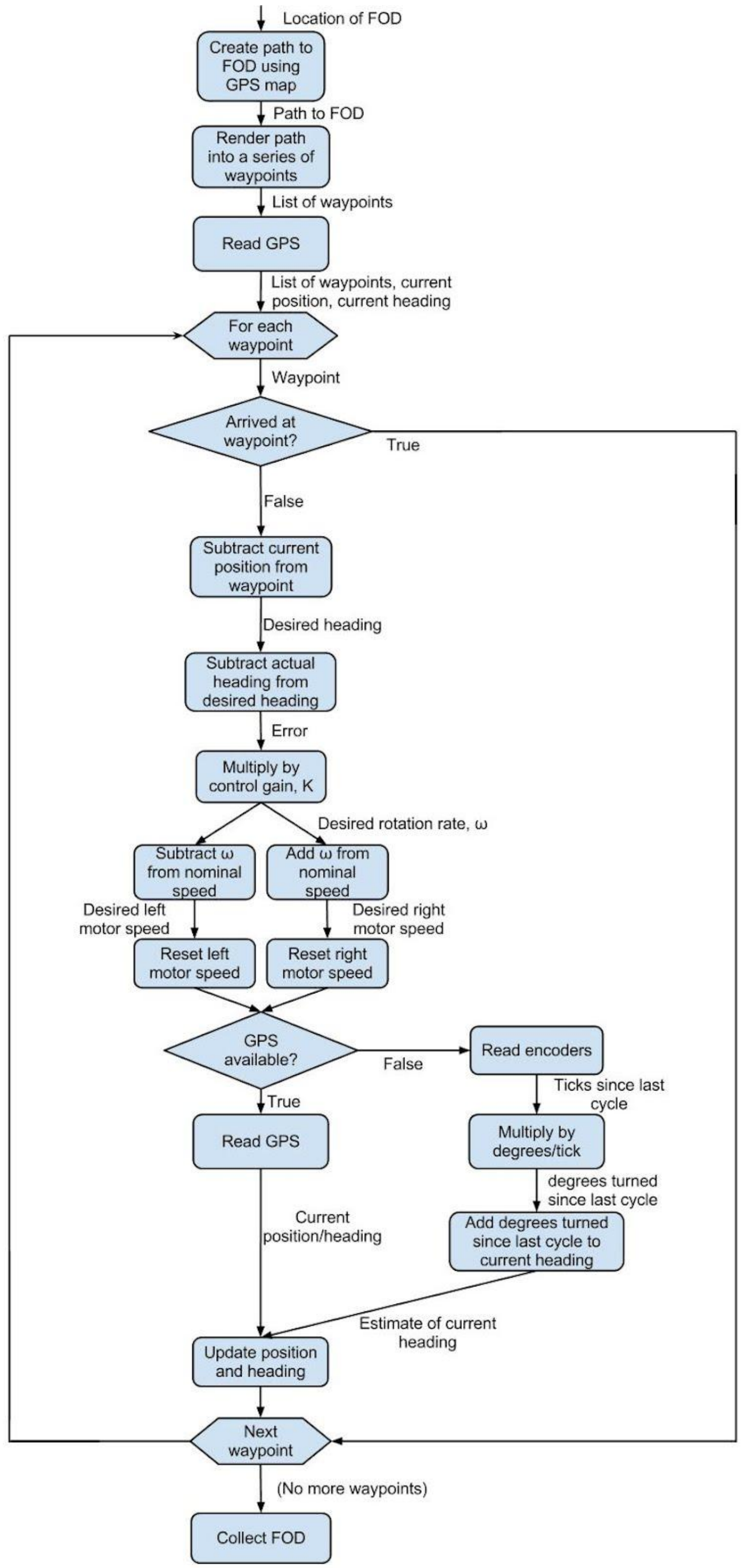


Figure 11: Schematic representation of navigation control algorithm

Operational Strategies

The FODHippo system will integrate seamlessly with current airport operations. Robot base stations will be scattered throughout the airfield, allowing rapid response to FOD across all airport surfaces, as shown in Figure 12.

Figure 12: Possible path to FOD from nearest base station

"GPS Fence" Strategy

In order to constrain the waypoint navigation of the robot, the system would include a virtual "GPS fence." The fence defines regions in which the robot is (or is not) safe to operate. There are three types of regions: "safe" regions, "neutral" regions, and "off-limits" regions. A safe region is one in which the robot is free to operate. The robot must still avoid other vehicles but is free to roam anywhere in the safe region. The robot must not operate in an off-limits region. If the robot is in an off-limits region there is a good probability that the robot has caused an incursion and it will be shut-down immediately. The neutral regions demarcate the borders between the safe regions and the off-limits regions. The neutral region provides a buffer-zone in the event of a navigation error. If a robot starts to wander too close to an active runway, for example, the neutral region gives the fail-safe GPS system time to re-route or shut down the robot before it causes an incursion.

The left side of Figure 13 shows an example of potential GPS fence regions at Boston Logan International Airport in which the runways are marked as off-limits, the taxiways and the stand are safe regions, and the border between safe and off-limits regions is neutral. The right side represents GPS fence regions in which the robot is allowed to move anywhere on the tarmac. This case might occur at low traffic times between aircraft movements.

Figure 13: Potential GPS fence regions

FOD Report System

We have prototyped a FOD report system to effectively compile and communicate all of the data that is collected during a FOD identification and retrieval run. The system stores every instance of FOD that is detected along with its latitude and longitude, time of detection, time of removal, and type of debris. The data is then overlaid on a map of the airport runway, as shown in Figure

14. By combining each set of data together, the system generates a virtual "heatmap" that visually depicts where on the runway FOD is most often found. Displaying the data in this way has two primary benefits. First, it provides an easy to understand view of all FOD occurrences. Second, it gives maintenance operations information regarding possible areas of the runway that might be degrading and becoming sources of FOD, allowing for more informed maintenance planning and for smarter placement of the robots' base stations.

Figure 14: FOD locations and corresponding heatmap

Safety Risk Assessment

Identification of Hazards and Risks

As part of the Safety Risk Management (SRM) process we conducted a safety risk assessment in order to identify potential hazards of our autonomous mobile FOD removal system. For each identified hazard, we found a number of associated risks, each with some severity and likelihood of occurring; the combination of the severity and likelihood determine the "level of risk" of a particular hazard.

Table 3 is a compiled list of the identified hazards and risks associated with implementing our autonomous FOD removal system. We've identified seven primary hazards; furthermore, we have assigned a certain probability, or likelihood of occurrence, to each hazard. Under each hazard, we determined that there are certain risks ranging from airport delays to catastrophic crashes. Each risk has its own associated probability given the specific hazard. The equivalent probability of a certain risk occurring is calculated by multiplying the probability of the hazard by the probability of the risk. For example, we have assigned the hazard of the robot creating FOD a probability of 1 in 100,000 (or 10^{-5}). The probability of a delay occurring given that the robot has created FOD is on the order of 1 in 10 (or 10^{-1}). Therefore, the equivalent probability of a delay occurring due because the robot created FOD is $10^{-1}*10^{-5} = 10^{-6}$ (or 1 in 1,000,000). This equivalent probability maps to a set of discrete likelihoods defined by the *FAA Safety Handbook*, which are shown in Table 4. The *FAA Safety Handbook* also defines levels of severity, which are shown in Table 5.

Table 3: Identified hazards and associated risks

Hazard and Associated Risks	Probability	Equivalent Probability	Severity	Level of Risk
[1] Robot fails on a runway	**10^-5**			
Delay	1	10^-5	negligible	low
Requires maintenance staff to remove rapidly	1	10^-5	minor	low
[2] Robot fails in a taxiway	**10^-5**			
Delay	10^-1	10^-6	negligible	low
Requires maintenance staff to remove rapidly	1	10^-5	minor	low
[3] Robot creates FOD	**10^-5**			
Delay	10^-1	10^-6	negligible	low
Engine Ingestion	10^-5	10^-10	minor	low
[4] Robot violates GPS fence (incursion)	**10^-5**			
Delay	10^-1	10^-6	negligible	low
Requires maintenance staff to remove rapidly	1	10^-5	minor	low
Catastrophic aircraft crash	10^-6	10^-11	catastrophic	medium
[5] Robot fails to collect FOD	**10^-3**			
Delay	1	10^-3	negligible	low
Requires maintenance staff to remove rapidly	1	10^-3	minor	low
[6] Lost communication with aborted robot	**10^-5**			
Delay	1	10^-5	negligible	low
Requires maintenance staff to remove rapidly	1	10^-5	minor	low
Catastrophic aircraft crash	10^-6	10^-11	catastrophic	medium
[7] Lose communication and control of robot	**10^-5**			
Delay	1	10^-5	negligible	low
Requires maintenance staff to remove rapidly	1	10^-5	minor	low
Catastrophic aircraft crash	10^-6	10^-11	catastrophic	medium
Damage to runway, signs, or airport itself	10^-2	10^-7	major	low
Totalled robot	10^-2	10^-7	minor	low

Key				
Equivalent Probabilty	Extremely Improbable	Extremely Remote	Remote	Probable
Severity	Negligible	Minor	Major	Catastrophic
Level of Risk	Low	Medium	High	

Table 4: Likelihood levels from FAA Safety Handbook

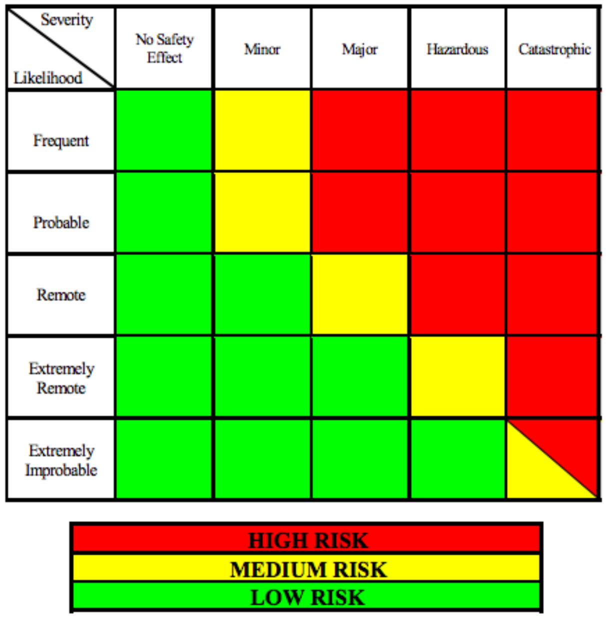
Probable	**Qualitative: Anticipated to occur one or more times during the entire system/operational life of an item. Quantitative: Probability of occurrence per operational hour is greater that 1 x 10^{-5}**
Remote	**Qualitative: Unlikely to occur to each item during its total life. May occur several time in the life of an entire system or fleet. Quantitative: Probability of occurrence per operational hour is less than 1 x 10^{-5} , but greater than 1 x 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 x 10^{-7} but greater than 1 x 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 x 10^{-9}**

Table 5: Levels of severity

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**

Finally, the equivalent probability or likelihood can be combined with the severity of a particular risk in order to get an overall “level of risk.” The “level of risk” has three discrete levels: low risk, medium risk, and high risk. A high risk level is an “unacceptable level of risk.” A proposal that contains a high risk level cannot be implemented until it is reduced to a lower level. A medium risk level is an “acceptable level of risk” and is the minimum acceptable safety objective. A proposal with a medium risk level may be implemented but it must be tracked and managed to ensure it remains at an acceptable level of risk. A low risk level is the target level of risk and is acceptable without restriction or limitation. Table 6 from the AC 150/5200-37 (“Introduction to Safety Management Systems (SMS) for Airport Operators”) defines the levels of risk in terms of likelihood and severity. [8]

Table 6: Levels of risk



Treatment of Risks

Having identified hazards and associated risks, we developed risk treatments to mitigate the risks and manage the hazards. We focused primarily on the medium risk levels since the low risk levels are generally acceptable. Our risk treatment strategies fall into two main categories: technical fail-safes and operational and managerial strategies.

Technical fail-safes mitigate the chance of the robot becoming a hazard due to a fault. For example, a redundant onboard GPS sensor, which operates on a separate power supply, would reduce the risk associated with the primary GPS sensor malfunctioning and causing the robot to violate a GPS fence, possibly causing an incursion. Along the same line, including a neutral zone between "safe" areas and "off-limits" areas would greatly reduce the chance of the robot accidentally causing an incursion. To mitigate the risks associated with losing control of the robot, we decided to employ a fail-safe "abort" system. An onboard master kill switch, which can cut power to the main robot, broadcasts a unique identifier on its own radio channel; if, for whatever reason, the main control station (off-board) loses contact with the master kill switch, the system attempts to power down the main robot via the main controller. If that is unsuccessful, the master kill switch activates and cuts the main power, thereby stopping the robot. This process can be seen in the flowchart in Figure 15 below.

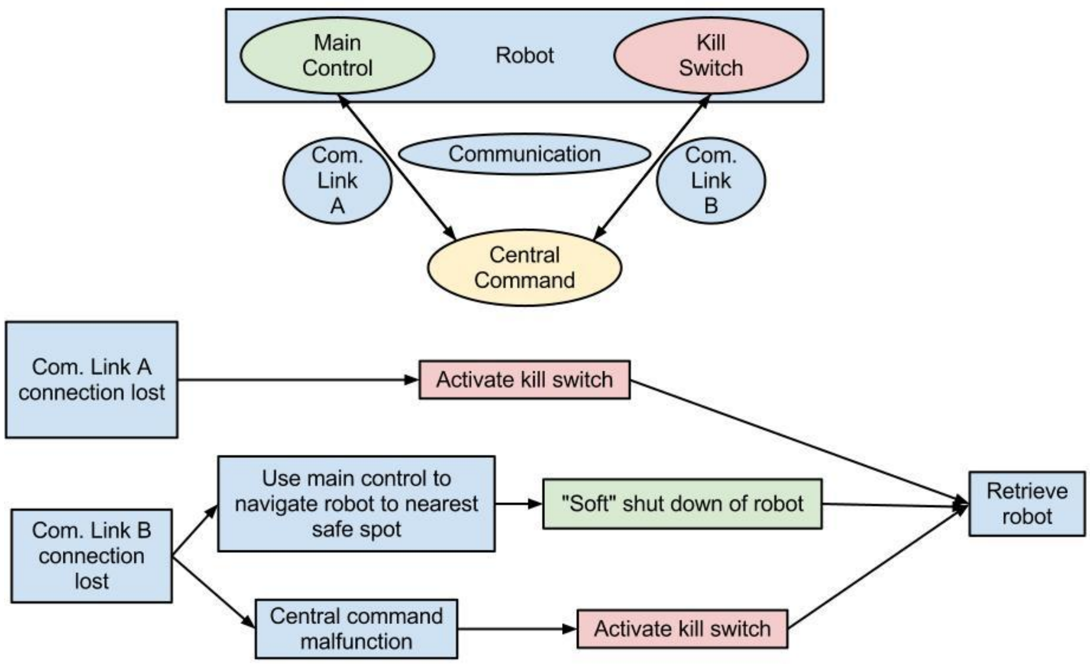


Figure 15: Failsafe system

A number of steps can also be taken on the operations side to better mitigate and treat risks as they occur. For example, properly training maintenance staff on how to quickly removing robots from the airfield would greatly reduce the risk of catastrophic failures.

Interactions with Airport Operators and Industry Experts

Our first interaction with an industry expert came in the form of a discussion with Professor Dan Hannon on September 23, 2011. During this discussion, Professor Hannon talked to us first about his own experiences with Massport and the Department of Transportation and then went on to outline a number of airport operational procedures and the various issues faced.

We met directly with representatives of Massport at Boston Logan International Airport in Boston, MA on November 10, 2011 and March 26, 2012 and also had some email correspondence.

Our first meeting with Massport was during the early stages of project planning and design and consisted of a general overview of the project goals and a discussion breaking down the functions of the airport. We spoke with Robert Lynch, the Airport Operations Manager, and Flavio Leo, the Manager of Aviation Planning, who were able to inform us about how often the airport encounters issues with foreign object debris (FOD) and how they handle the issues. After extensive discussion about how airports function and handle issues on a daily basis, we were taken out to the tarmac for a tour of the Logan Airport runways. This firsthand experience allowed us to see exactly what terrain and issues we would have to overcome in order to design a successful prototype. We were also able to receive feedback on various potential solutions; this firsthand information proved to be invaluable when moving forward with the design. [13] [14] Additionally, while out on the airport surface, we had the opportunity to interact with an engineer from Xsight Systems who was working to install the detection hardware on Logan's runway 9, which sees 35% of all departures from the airport. [13] [14] He informed us of many of the system's capabilities, allowing us to better understand the potential for integration with our proposed system.

Figure 16: Second Logan meeting; from left to right, Flavio Leo, Check Crescenzo, Nick Stone, Vinnie Cardillo, and Will Langford

After completion and testing of the first prototype we met with Robert Lynch, Flavio Leo, Chuck Crescenzo, and Vinnie Cardillo at Boston Logan International Airport in March, shown above in Figure 16. When this meeting occurred we had already begun research and planning for further work beyond the original prototype. The robot was presented to the Massport officials during a meeting where successes and shortfalls of the robot were discussed as well as possible areas of improvement. Afterwards, we were able to bring the robot out to the airport runway for a demonstration. The Massport officials provided us with actual FOD that had been removed from the runway earlier in the week and observed the capability of the prototype to successfully retrieve the FOD (see Figure 17 below). It was not entirely successful in navigating the rough terrain of the runway, but was able to capture and remove the debris that it did reach. This demonstration reinforced our intuition that a successful model would need a larger and more robust design that is able to traverse the grooved terrain of the runway and the adjacent lawn. During this meeting, Massport officials gave us positive and constructive feedback on both the existing system and our future plans, as well as providing additional possible usage modes that could be incorporated to add functionality to the system.

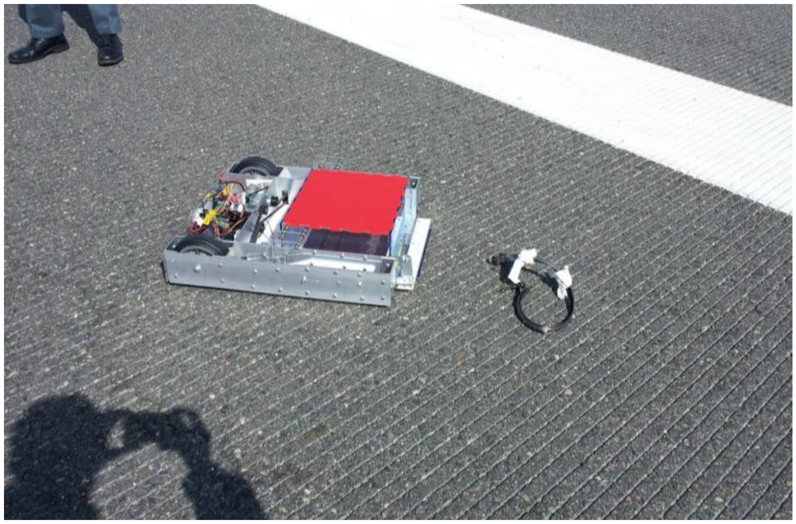


Figure 17: FODHippo on the runway at Logan Airport with FOD

Projected Impacts of Design

Cost Benefit Analysis

There are both direct and indirect costs of FOD. The direct costs primarily consist of FOD related engine damage as debris is sucked into the engine intake. A study of the economic costs associated with FOD undertaken by Insight SRI found that engine damage related to FOD made up roughly eighty-percent of the total direct cost; furthermore, the study showed that engine maintenance due to FOD cost the industry $205,000 per 10,000 aircraft movements. A large airport, like Boston Logan International Airport, has approximately 400,000 aircraft movements per year. This means that the direct cost of FOD at an airport like this may be upwards of $8M. [1]

Indirect costs of FOD are largely associated with airport delays. The Insight study found that delays due to FOD constitute 667 minutes of delay per 10K aircraft movements and have an associated cost of $26,740 per 10K movements. [1] For an airport with 400,000 movements this entails a cost of over $1M.

Our system effectively mitigates both of these major costs of FOD. The direct costs are reduced by doing FOD checks in the taxiway more frequently than would otherwise be done. Because the system is automated, there is negligible cost associated with operating the system more frequently, especially if the additional sweeps are done when there is little traffic. This means that the runways and taxiways can be checked for FOD more often. The Insight study suggests that roughly 40% of FOD related damage to engines occurs in the taxiway (with 50% occurring in the runway and 10% in the stand). [1] Assuming that FOD related incidents are roughly proportional to the amount of time FOD is left on the tarmac, it is clear that by reducing the amount of time FOD is left exposed on runways it is possible to reduce the risk of FOD engine ingestions and other FOD-related damages. The FODHippo does precisely this. It is safe to assume that the taxiway may be checked twice as often with the FODHippo system compared to conventional human checks. Given this increased detection frequency, along with the fact that 40% of engine damage due to FOD occurs in the taxiway, the FODHippo conservatively provides a 20% reduction in FOD related engine ingestion incidents. This effectively entails a cost savings of $1.6M per year given the $8M total direct cost of FOD.

The indirect costs of FOD are reduced by expediting the FOD removal process and reducing delays. Based on conversations with Massport officials, we estimate the standard FOD removal time to be roughly ten minutes. The target round-trip retrieval time of the FODHippo system, on the other hand, is three minutes. Assuming the FODHippo can travel at 30 mph, four robots may be placed on a 2-mile runway, for example, to keep the maximum round-trip time to less than three minutes (assuming one minute is spent collecting the debris itself). This reduction in retrieval time constitutes a 70% reduction in delays due to FOD and, given the $1M total cost of FOD related delays, saves $700K per year.

We estimate the cost of the FODHippo system installation to be approximately $2M. This cost is made up of the cost of each robot and base station unit as well as installation costs and certification costs. Each robot and base station will cost roughly $40K together. A large airport like Logan International Airport may require upwards of 20 robots and base stations to ensure a retrieval time of less than three minutes for each runway (assuming there are five runways); this constitutes a cost of $800K. Together, installation and certification costs may be upwards of $1.5M. Installation costs are associated with establishing the communication infrastructure, training staff to work with the robots, and installing the actual hardware in the airfield. The certification of the system is necessary to ensure the safety of the robots and the operating system. The total cost comes out to $2.3M.

Another advantage of the FODHippo system is its scalability. After the initial investment in support infrastructure and setup, it will be very easy to add additional units for an increase in efficiency at a small incremental cost. When making the decision to use the FODHippo technology, an airport may to decide to initially install only a few units in addition to the main systems necessary to test the system on one runway. While the startup cost for integrating the FODHippo system into a new airport is a large undertaking, it is very easy to increase the number of units once the system is in place. This will allow airports to easily expand their autonomous coverage area after they become comfortable with the technology for a further decrease in response time for FOD removal.

Commercial Viability

We believe that this product could be prepared for commercial use by first continuing to iterate prototypes until a fully functional device was realized and then optimizing the design for manufacturability. As the final product will most likely be approximately 5 feet long and have a top speed of 30 miles per hour, the final design will have to be quite robust. In addition, relatively small production volume will most likely require the device to be assembled mostly by hand. We envision manufacture of the final product consisting mostly of bolting off-the-shelf components to a welded aluminum chassis. This methodology should result in relatively low startup costs, appropriate to the foreseen production volume, as well as ensure easy procurement of replacement parts.

In order to provide the system to airports, we need be able to make a profit. At $40K per robot with 10 robots and an installation cost of $100K, the cost to us is roughly $500K per installation at a large airport; this provides us with $1.5M in gross profit per installation. We anticipate considerable costs in development due to the required certification and safety verification. For this reason, development costs (with 10 employees for three years) are anticipated to be roughly $8M. If we were to install in two airports, the break-even point would occur after four years, as seen in Table 7 and Figure 18.

Table 7: Projected 10-year financial breakdown (thousands of dollars)

Year	# of employees	# of Airports	Costs	Revenue	Profit	Net Income
0	10	0	7400	0	-7400	-7400
1	10	1	1050	2400	1350	-6050
2	10	1	1050	2400	1350	-4700
3	20	2	2100	4800	2700	-2000
4	20	2	2100	4800	2700	700
5	20	3	2350	7200	4850	5550
6	25	4	3000	9600	6600	12150
7	30	5	3650	12000	8350	20500
8	35	6	4300	14400	10100	30600
9	40	8	5200	19200	14000	44600
10	50	10	6500	24000	17500	62100

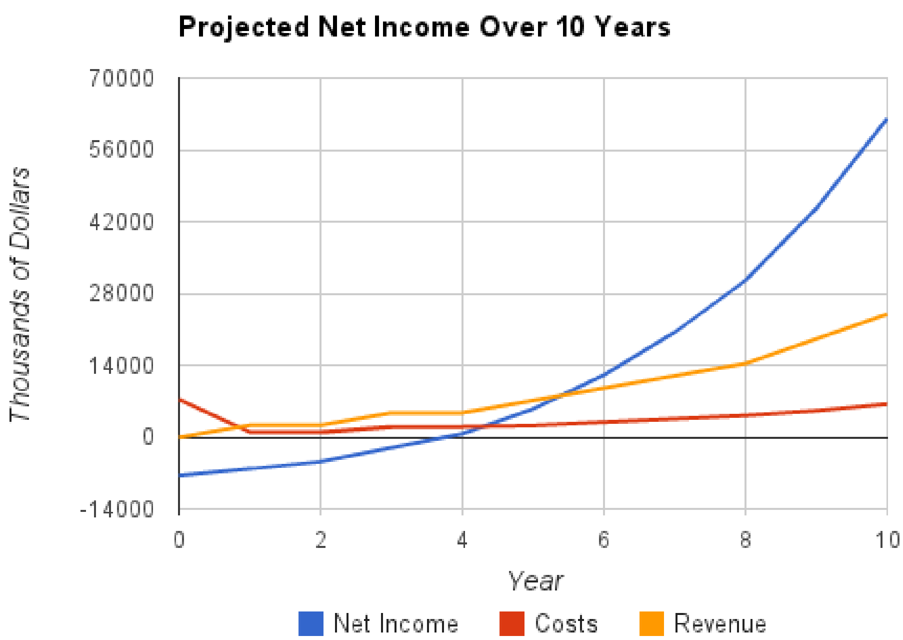


Figure 18: Projected 10-year financial breakdown

Conclusion

Over the course of this report we have described our vision of a distributed, autonomous FOD removal system. We have presented our significant body of completed work as well as a detailed outline of the steps necessary to both develop the existing design into a commercial product and integrate this product into existing airport operations. From our functioning prototypes to our profitable cost analysis, every aspect of this report reflects both the efficacy and usability of our design. Many of the design choices lend themselves to a robust fully integrated system. The system's modular nature, through the use of multiple robots spread throughout the airport surface, allows for more efficient removal of debris, easier replacement of failed components, and a more cost-effective expansion of the system. The decision to use off-the-shelf components when available, as well as the one degree of freedom retrieval actuation, results in a robot that is simultaneously sturdier and easier to maintain. In short, we believe we have presented a viable system that reduces the impact of one of the airline industry's biggest problems.

Appendix A - Contact Information

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Appendix B - Description of Tufts University

Tufts University is a small research university (with the feel of a liberal arts college) spread across three Massachusetts campuses in Medford/Somerville, Boston, and Grafton, along with a satellite campus in Talloires, France.

Tufts' main campus straddles the municipalities of Medford and Somerville and is a short T ride from downtown Boston. This campus contains all of the school's undergraduate programs, as well as the Fletcher School of Law and Diplomacy, the Graduate School of Engineering, and the Graduate School of Arts and Sciences. The Boston campus, located in Boston's Chinatown neighborhood, houses Tufts' medical and dental schools, as well as the Friedman School of Nutrition and the Sackler School of Biomedical Sciences. Tufts' final school, the Cummings School of Veterinary Medicine, is in Grafton, located in central Massachusetts.

The school's undergraduate enrollment is approximately 5,100 students, of which the School of Engineering accounts for 800. Across all three campuses, there are about 4,400 graduate and professional students, bringing the total number of students enrolled at Tufts to 9,500. The School of Engineering offers 10 accredited bachelor of science degrees; the four students on the FODHippo team are all pursuing a bachelor of science in Mechanical Engineering.

The Department of Mechanical Engineering has seventeen faculty members specializing in all fields of Mechanical Engineering. Faculty are engaged in a number of different research areas, ranging from soft robotics and GPS navigation to cryogenics and aerogels. The university's interdisciplinary nature affords opportunities for collaboration not only with other departments within the School of Engineering, such as the Department of Biomedical Engineering, but with researchers at all of the university's schools, such as the medical school.

Appendix C - Description of Massport

Over the course of the project's development, we worked closely with the Massachusetts Port Authority, known as Massport. Massport owns and operates three airports and a seaport: Boston Logan International Airport, Worcester Regional Airport, Hanscom Field, and the Port of Boston. Massport was created by the Massachusetts State Legislature in 1959.

Boston Logan International Airport is located in East Boston, MA. Employing 12,000 workers and operating six runways, Logan is New England's largest airport and is ranked as the 20th airport in the nation for passenger volume and 19th for airport movement. The airport covers approximately 1,700 acres. Originally called Boston Airport, it was built in 1923 on tidal flats by the U.S. Army and renamed for General Edward Lawrence Logan 1943.

Logan Airport stimulates the New England economy by generating $7 billion every year, having transported 28 million passengers in 2011. There are more than 100 non-stop domestic and international locations available from Logan flying on almost 50 airlines.

The main control tower at Logan Airport is 22 stories (285 feet) tall. This tower was erected with twin cylindrical pylons in 1973 at a cost of $7.3 million.

Appendix E - Evaluation of Educational Experience

1. Did the FAA Design Competition provide a meaningful learning experience for you? Why or why not?

The FAA Design Competition for Universities provided a great educational experience for all of us. As we will elaborate on below, we each gained invaluable experience in brainstorming and working on a team, trying to find solutions to a real world issue, fabricating prototypes and dealing with both the design phase and the debugging phase, and the opportunity to present our ideas in a professional venue (both orally and on paper).

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

In addition to the challenges inherent in any engineering design process, we faced several key challenges in this project that stand out.

One major challenge was the lag time between the start of the project and our first meeting with Robert Lynch and Flavio Leo at Massport, which didn't occur until November 10th, roughly 2 months into the semester. We luckily had access to Professor Hannon's knowledge of the field, as well as numerous FAA Advisory Circulars, which both proved incredibly useful in our initial phases of defining the problem, sketching preliminary specifications, and starting to conceptualize our solution. Due to these resources we were able to have a solid understanding of the problem and a good amount of progress towards our solution by the time we were able to meet with Massport.

This contributed to another major challenge, which was the short time period we had to manufacture our first prototype. By making extensive use of SolidWorks, especially motion studies, we were able to isolate potential issues prior to fabrication and select the appropriate parts. We also were lucky to have help from Jim Hoffman, the manager of the Department of Mechanical Engineering's machine shop, while we were cutting, drilling, milling, and lathing the various parts and materials that went into our prototype.

A major issue in the second semester was our lack of funding, as our Senior Design capstone course was only during the fall semester. We had originally hoped to build a more involved second prototype, incorporating both the navigation and the removal subsystems in a larger, more robust package. We applied for funding from the School of Engineering and weren't awarded a grant until late in the semester, at which point it was too late to spend the money. We refocused our efforts instead on building a small but robust robot from the parts we had on hand so we could develop the necessary navigation algorithms and continue exploring other aspects of our system.

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

After our initial conversation with Professor Hannon, an industry expert, about the various issues that airport operators are concerned about, we discussed which ones interested us and ways we might solve them. After considering which problems lined up well with our capabilities, we decided to focus on FOD detection and removal.

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

It was very helpful to talk to industry professionals to hear recommendations and concerns with what went well and what to improve. No book or research paper could compare to the feedback from professionals in the field that work with FOD issues on a daily basis. We were able to use our first meeting to create specifications for our prototype, and at our second meeting we were able to actually test our prototype on the Boston Logan International Airport runway. Getting customer feedback is an important part of any engineering design process, so getting the opportunity to meet with actual airport experts, which we likely wouldn't have had otherwise, was a great experience.

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?

This project helped us learn some skills while strengthening others. We were challenged to solve physical problems during the design and manufacturing process and we worked to overcome software issues during programming and debugging phases of our project as well during the presentation of our findings.

During the design and fabrication process of FODHippo, there were many times where we were reminded how crucial it was to keep a comprehensive and detailed record of what we had done and what needed to be done. From selecting the parts and materials we were using, to choosing connection types and sizes, and eventually to the assembly process, we gained a great deal of respect for how many decisions and seemingly insignificant tasks go into the design process.

We were afforded an opportunity to apply many of the skills we'd been taught in our other classes, from electronics to mechanical design to coding, in a real project. Along with learning to apply our skills, we picked up some more along the way, such as how much thought needs to go into the process for selecting parts and how to effectively debug a system combining hardware and software.

This project taught us that a mechanical design can only be successful if all of the necessary software aspects function properly, and that one successful test run does not qualify a prototype as a success. It was necessary to do extensive debugging and testing before presenting our design, and we made sure that we were prepared. We learned how important communication and distribution of tasks were in order to create an efficient group environment. We gained experience with organizing our ideas into succinct presentations to not only focus our material, but also to strengthen our ability to convey information in a concise manner.

For all of these reasons, this project helped us establish the skills and knowledge we need both to pursue further study and to eventually launch successful careers.

Faculty Evaluation (G. Leisk and J. Rife)

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

In the capstone design experience in the Mechanical Engineering Department at Tufts University, the goal is to expose students to open-ended design challenges with real-world applications. The competition complements the student educational experience in a number of ways.

- The FAA Competition presents relevant, challenging, real-world problems that provide a rich design space for student innovation.
- The recognition and awards associated with the competition provide added motivation for students to go beyond course requirements to outshine other competitors.
- The ability to visit with operators and see the design environment is an invaluable experience for the students. In the case of our team, students learned an enormous amount about airport operations from their discussions with Massport representatives and from the opportunity Massport provided to the students to field their robotic system on an inactive runway at Logan airport.

- The competition's emphasis on system engineering further complements the student learning experience. In our mechanical engineering program, we generally emphasize product design, with projects producing a tangible, working prototype. In order to field an entry for the FAA competition, students had to go one step farther, considering a whole-system analysis involving many interacting components, safety issues, training, maintenance, etc.

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

The students undertook this competition effort as their Senior capstone project in Mechanical Engineering. A subset of the students extended their efforts through subsequent independent studies, for credit.

The challenging project the students focused on had all of the key educational elements that capstone experiences should present: open-ended design challenge (no off-the-shelf solutions exist), customer-oriented problem, required knowledge from various disciplinary areas of Mechanical Engineering, and necessitated good organizational skills and use of design tools. The student team thrived on the project and were awarded the Department's James O'Leary Design Award (awarded each year to a Senior undergrad team that has excelled in a design effort).

3. What challenges did the students face and overcome?

The students faced two key challenges. The first challenge was to schedule an initial visit to Logan Airport and meet with relevant operators to gather detailed information on the design challenge they were tackling. It took some time to coordinate a visit; however, the team utilized the delay to conduct background research and to start developing preliminary ideas for solving the stated problem. When a trip to Logan Airport took place, the operators were extraordinarily helpful in discussing operational issues and showing the team and mentors the runways and other aspects of the design environment. The students were able to share their initial ideas and get immediate feedback. The second challenge involved a live demonstration of an early working prototype. In a follow-up visit to Logan Airport, live testing of the prototype highlighted a few design issues that only became apparent in the actual design environment. This valuable experience helped to direct the team to make several design improvements.

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

The FAA Design Competition will be a perennial source for capstone design experiences at Tufts University. The educational value, real-world design challenges, and competition format are all motivational elements.

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

The FAA Design Competition for Universities is typically announced close to Labor Day, which is at the beginning of the Fall semester for most universities. One of the important initial design activities is to visit airport operators and/or companies and experts to gather background information on the problem(s) and existing solutions. The late announcement date of the Competition makes it difficult on instructors to pre-plan to organize student team(s) and to initiate the aforementioned initial design activity in a timely manner. Ideal timing of the announcement would be in late Spring or early Summer.

Appendix F - References

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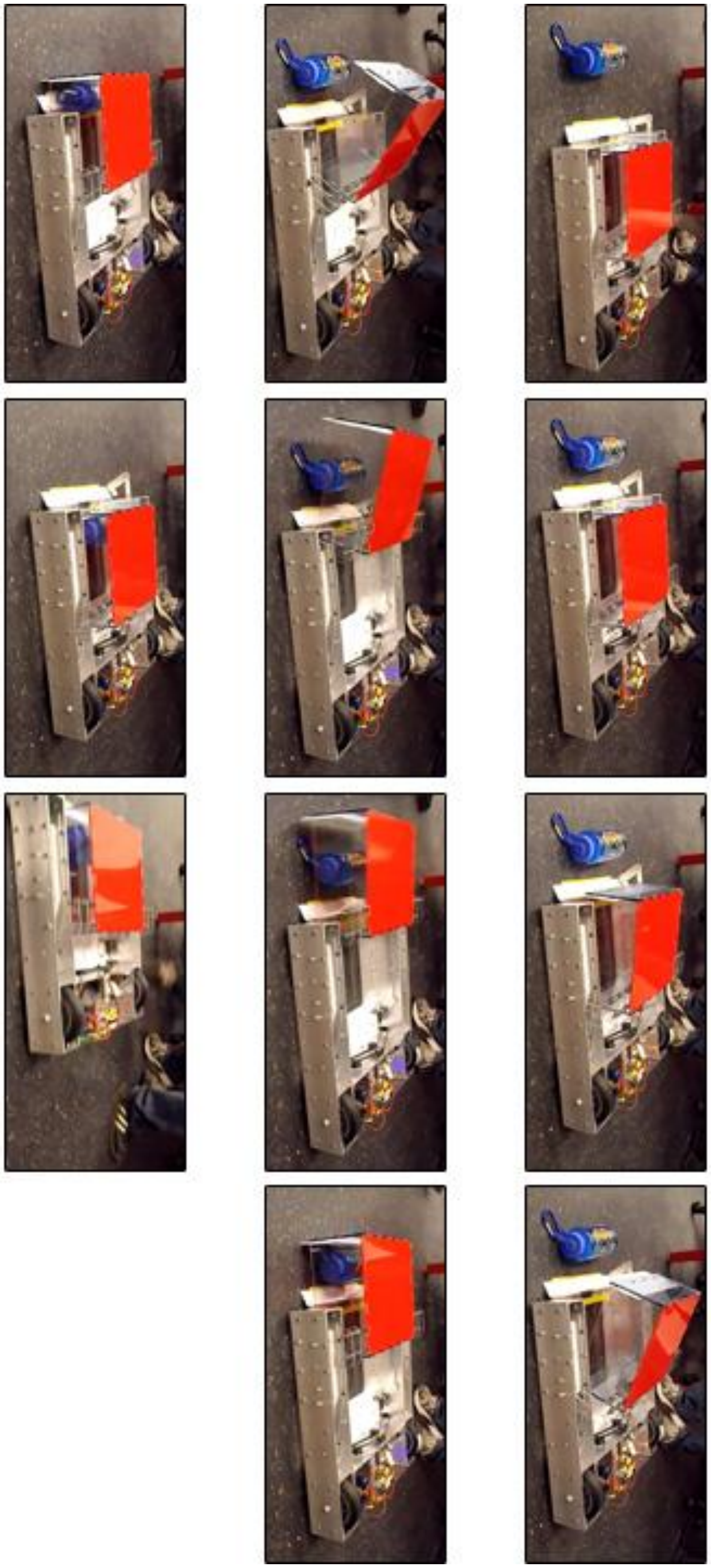
Appendix G - FODHippo in Action

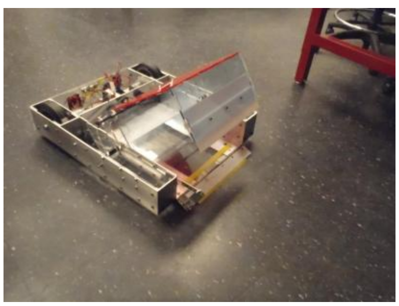


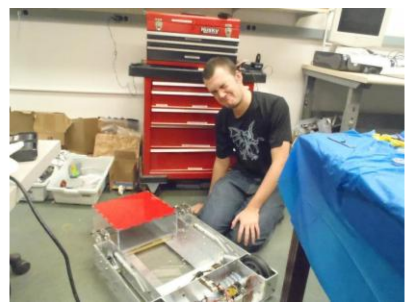
Appendix H - Additional Photos

First Logan visit

Xsight's FOD detection system in place at Logan

Assembly of first prototype



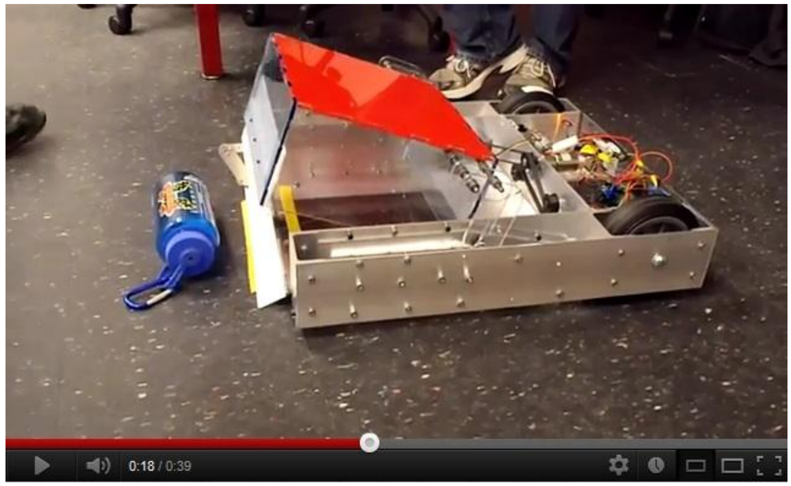


Second Logan visit

Appendix I - Links to Videos

First Prototype

http://youtu.be/JALfnCEsUK4

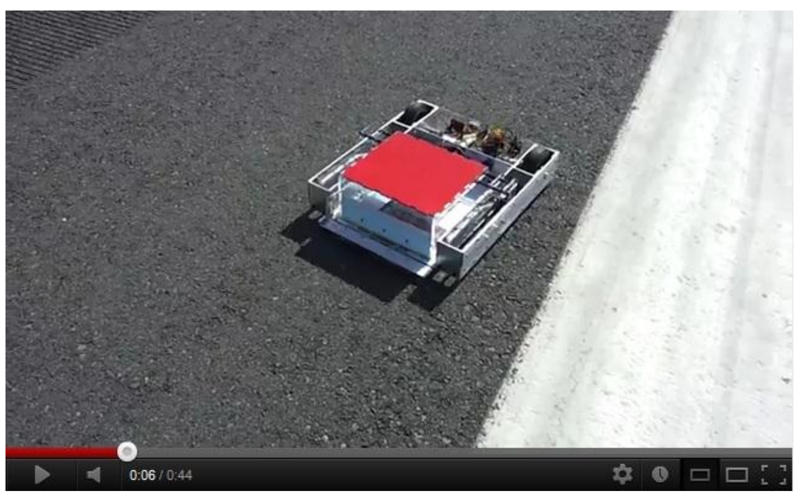


GPS Navigation

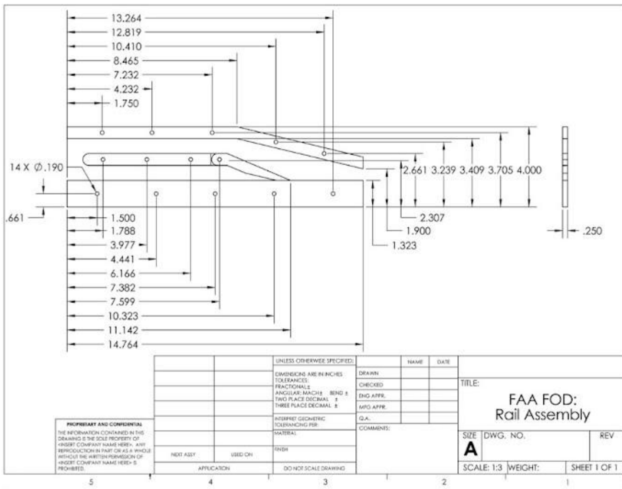
http://youtu.be/yql4bbO7Dg4

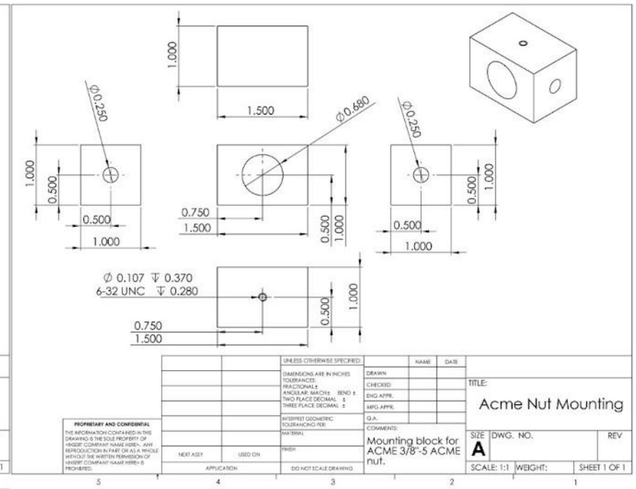
Second Logan Trip

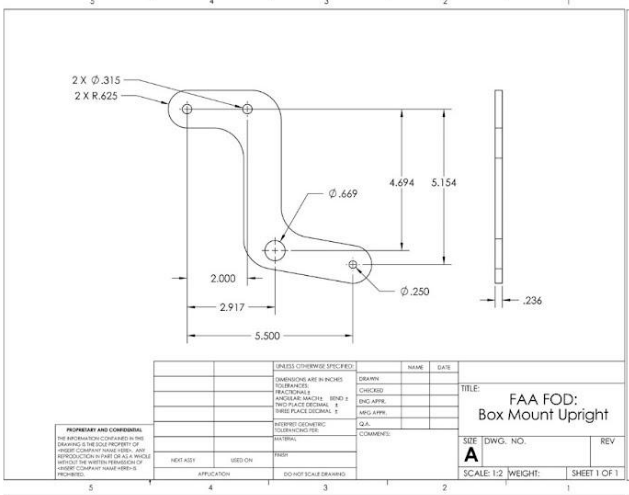
http://youtu.be/V-WQPh7PRK0

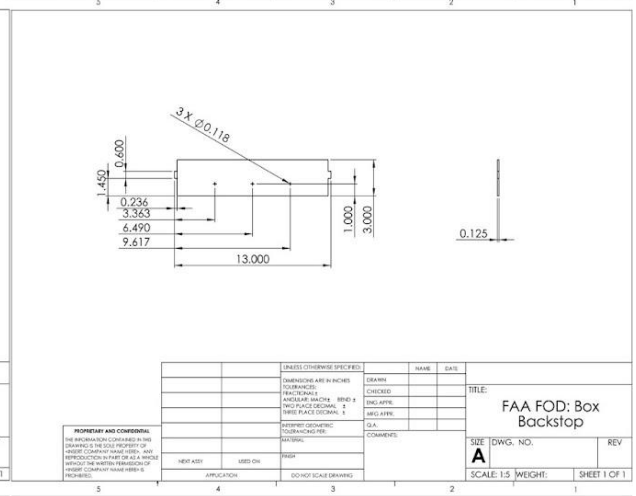


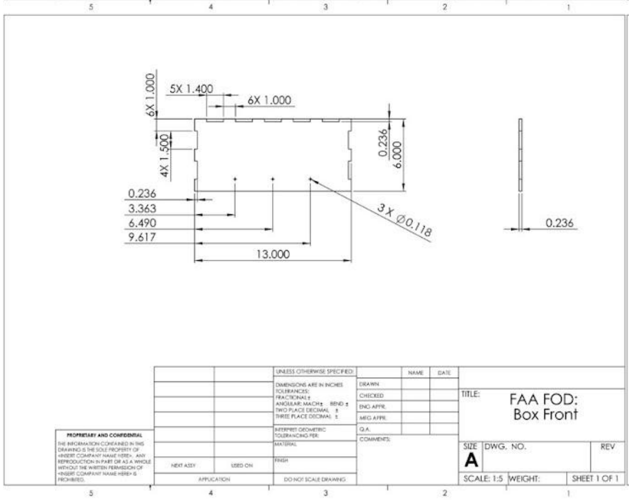
Appendix J - Detailed Drawings (not to scale)

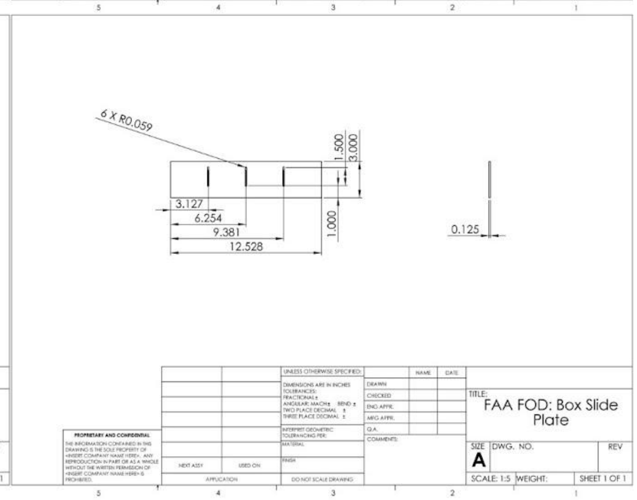


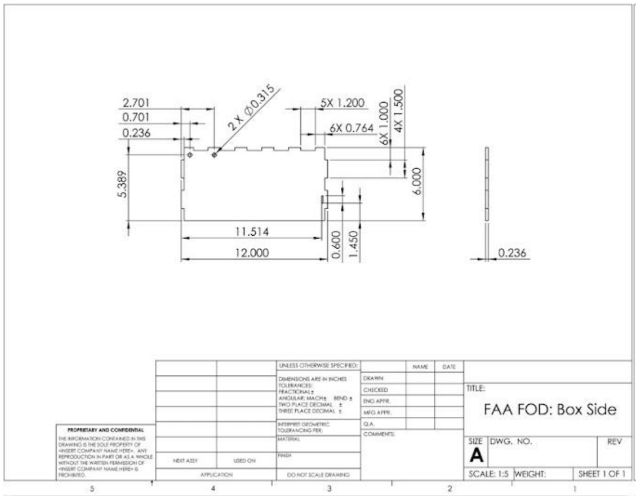


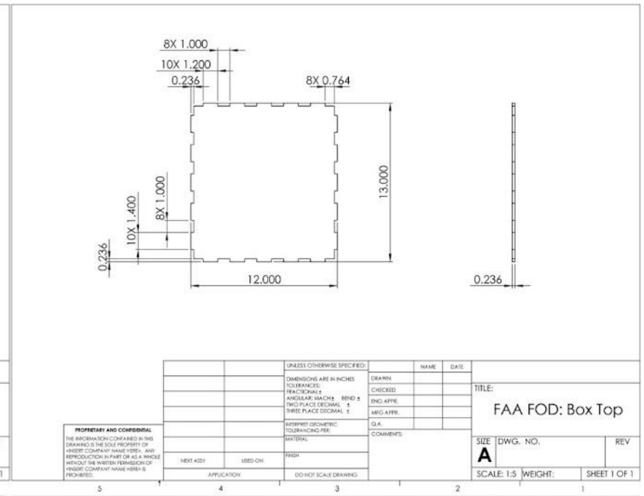


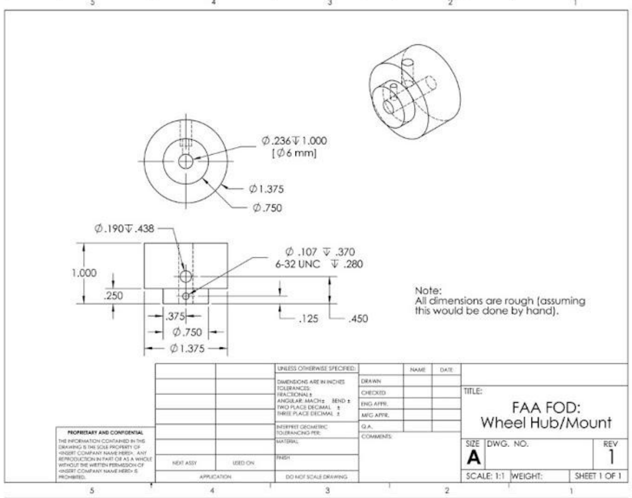


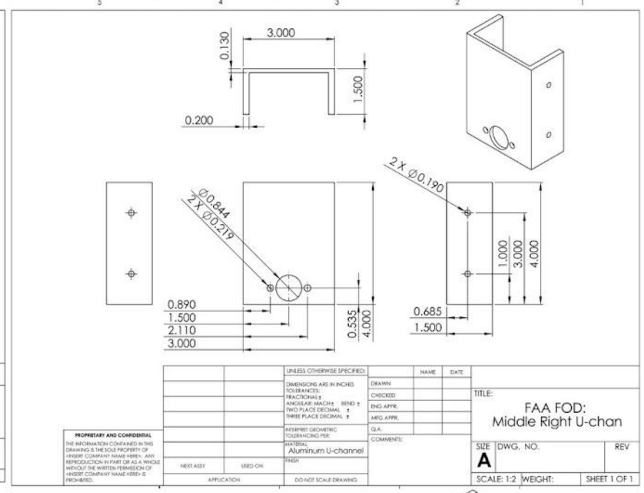


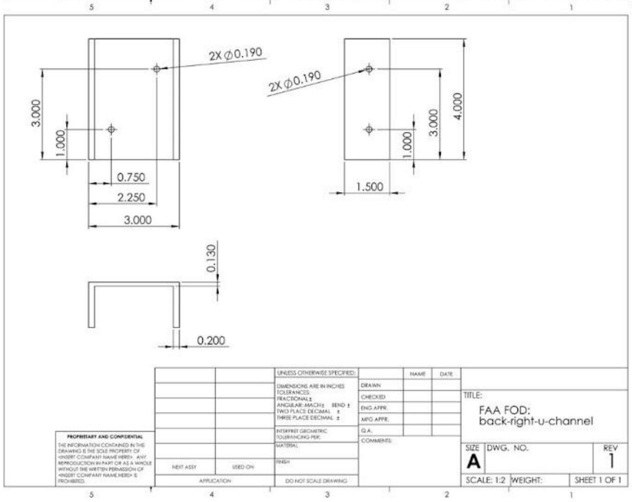


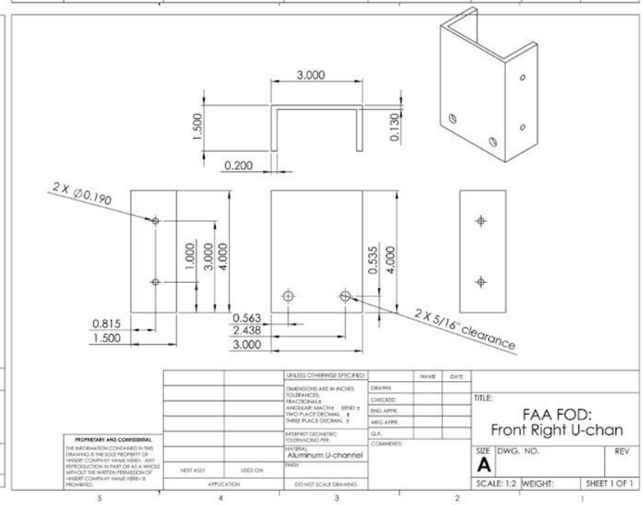

FAA FOD: Box Side
SCALE: 1:5
SHEET 1 OF 1

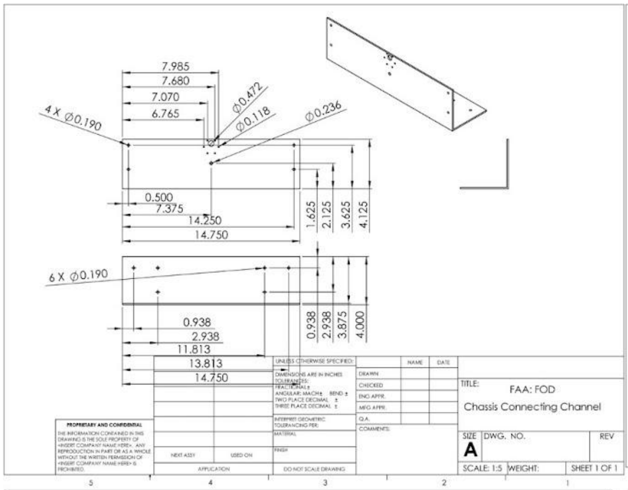

FAA FOD: Box Top
SCALE: 1:5
SHEET 1 OF 1

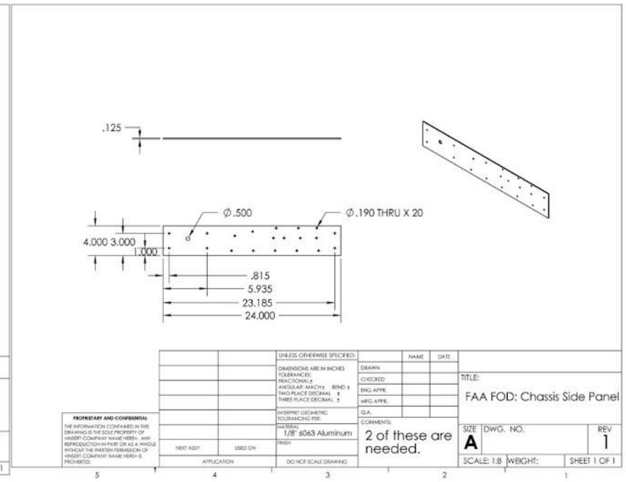

Note:
All dimensions are rough (assuming this would be done by hand).
FAA FOD: Wheel Hub/Mount
SCALE: 1:1
SHEET 1 OF 1

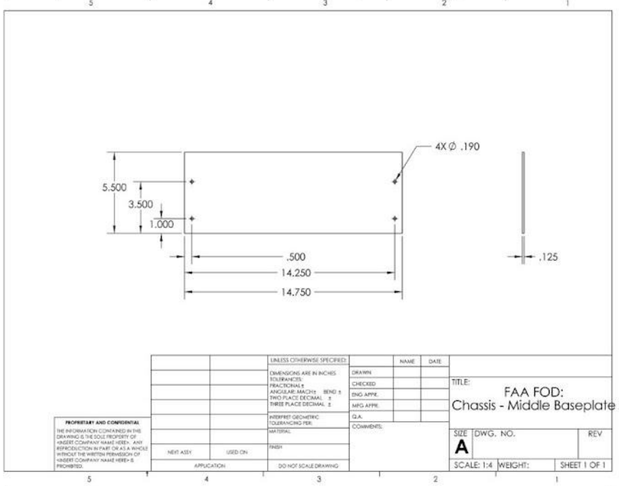

Aluminum U-channel
FAA FOD: Middle Right U-chan
SCALE: 1:2
SHEET 1 OF 1

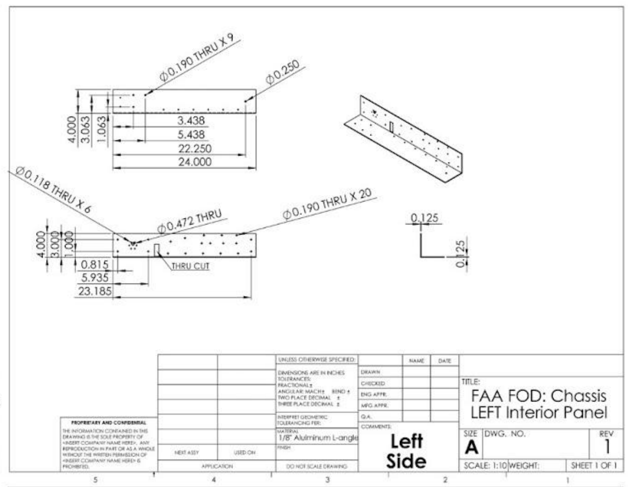

FAA FOD: back-right-u-channel
SCALE: 1:2
SHEET 1 OF 1

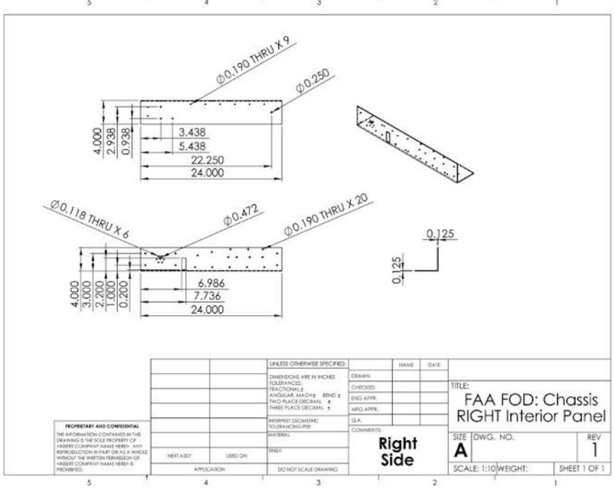

2 X 5/16" clearance
Aluminum U-channel
FAA FOD: Front Right U-chan
SCALE: 1:2
SHEET 1 OF 1

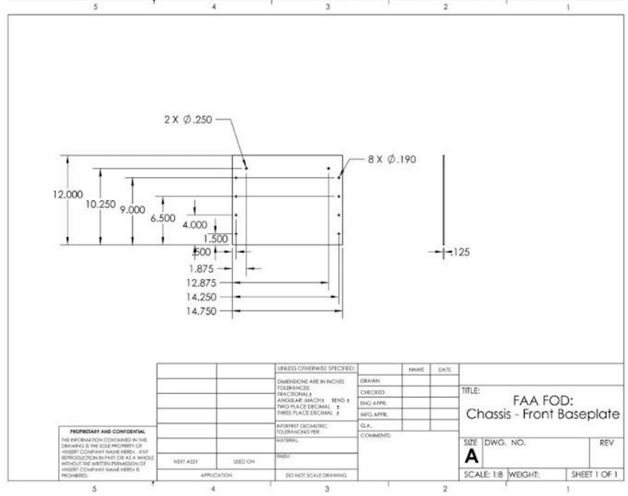

7.985
7.680
7.070
6.765
4 X ∅0.190
∅0.472
∅0.118
∅0.236
0.500
7.375
14.250
14.750
1.625
2.125
3.625
4.125
6 X ∅0.190
0.938
2.938
11.813
13.813
14.750
0.938
2.938
3.875
4.000
TITLE:
FAA: FOD
Chassis Connecting Channel
SIZE A
SCALE: 1:5
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL


.125
∅.500
∅.190 THRU X 20
4.000 3.000
1.000
.815
5.935
23.185
24.000
MATERIAL:
1/8" 6063 Aluminum
2 of these are needed.
TITLE:
FAA FOD: Chassis Side Panel
SIZE A
REV 1
SCALE: 1:8
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL


4X ∅ .190
5.500
3.500
1.000
.500
14.250
14.750
.125
TITLE:
FAA FOD:
Chassis - Middle Baseplate
SIZE A
SCALE: 1:4
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL


∅0.190 THRU X 9
∅0.250
4.000
3.063
1.063
3.438
5.438
22.250
24.000
∅0.118 THRU X 6
∅0.472 THRU
∅0.190 THRU X 20
4.000
3.000
0.815
5.935
23.185
THRU CUT
0.125
0.125
MATERIAL:
1/8" Aluminum L-angle
Left Side
TITLE:
FAA FOD: Chassis LEFT Interior Panel
SIZE A
REV 1
SCALE: 1:10
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL


∅0.190 THRU X 9
∅0.250
4.000
2.938
0.938
3.438
5.438
22.250
24.000
∅0.118 THRU X 6
∅0.472
∅0.190 THRU X 20
0.125
0.125
4.000
3.000
2.200
1.000
0.200
6.986
7.736
24.000
Right Side
TITLE:
FAA FOD: Chassis RIGHT Interior Panel
SIZE A
REV 1
SCALE: 1:10
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL


2 X ∅ .250
8 X ∅ .190
12.000
10.250
9.000
6.500
4.000
1.500
.500
1.875
12.875
14.250
14.750
.125
TITLE:
FAA FOD:
Chassis - Front Baseplate
SIZE A
SCALE: 1:8
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL

Appendix K - Parts for First Prototype

Part	Supplier	Part Number	Quantity	Total Price
Martin Flat-Free Rubber Wheels	RobotMarketplace	ZP61RT-325	2	$23.98
Dual VNH2SP30 Motor Driver	Pololu	708	1	$59.95
19:1 Metal Gearmotor w/ Encoder	Pololu	1442	2	$79.90
37D Metal Gearmotor Bracket Pair	Pololu	1084	1	$7.95
Needle Roller Brng for 3/8" Shaft	McMaster-Carr	1434K25	2	$16.46
Acme Round Nut 3/8"-5 Sz	McMaster-Carr	95075A101	2	$62.44
Precision Acme Threaded Rod 3/8"-5	McMaster-Carr	99030A100	1	$34.62
Surface Hinge W/Holes Removable Pin	McMaster-Carr	1586A12	2	$11.56
Round Head Machine Screw 1/2"-13 (10 pack)	McMaster-Carr	90276A712	1	$5.16
Ball Bearing for Shaft Diameter 3/8"	McMaster-Carr	7208K51	2	$42.36
Socket Set Screw 6-32 Thread (pack)	McMaster-Carr	92313A144	1	$2.78
Acetal Resin Rod 3/4" Diameter	McMaster-Carr	8576K18	5 ft.	$14.75
Aluminum (Alloy 6061) 1-3/8" x 1'	McMaster-Carr	8974K171	1	$11.63
Acrylic Sheet .236" Thick, 12" X 24",	McMaster-Carr	85635K533	3	$52.89
10-32 Round Head Phillips Machine Screw (100 pack)	McMaster-Carr	90272A829	2	$8.44
10-32 Hex Nut (100 pack)	McMaster-Carr	90545A111	2	$4.56
Aluminum (Alloy 6063) 90 Deg Angle, 1/8" X 4" X 4", 8' L	McMaster-Carr	88805K67		$65.10
Stud-Mount Ball Transfer Std, 5/8" Steel Ball	McMaster-Carr	6460K21	2	$13.34
Threaded Rod M8 Size, 1 Meter Length, 1.25 mm Pitch	McMaster-Carr	99055A125		$4.29
Aluminum (Alloy 6061) U-Channel, 3"X 1-1/2", 3' L	McMaster-Carr	1630T311	1	$24.23
Aluminum (Alloy 6061) 1/8" Thick X 4" Width X 6' Length	McMaster-Carr	8975K16	1	$30.83
Aluminum (Alloy 6061) 1" Square, 1' Length	McMaster-Carr	9008K141	1	$11.99
Clear Cast Acrylic Sheet .125" Thick, 12" X 24"	McMaster-Carr	8560K257	2	$29.66
28 Teeth Timing Pulley 3/8" bore	SDP-SI	A 6Z53-028DF0912	2	$12.16
28 Teeth timing pulley 6mm bore	SDP-SI	A 6Z53M028DF0906	3	$18.24
350 Teeth, 9mm (.354) Wide Belt	SDP-SI	A 6R53M350090	1	$16.42
Pitsco DC Drive Motor	Tetrix	W39083	1	$29.95
HiTec HS-485HB Standard Servo	Tetrix	HS-485HB	1	$14.95
Sparkfun Ardumoto	Sparkfun	DEV-09815	1	$24.95
Wixel Arduino Shield + Wixel Pair + USB Cable	Pololu	2501	1	$49.95
Arduino Uno	Pololu	1616	1	$29.95
		Subtotal:		$815.44

Appendix L – Embedded GPS Navigation Code

local_ezmotor.h:

```
#ifndef ARDUINO_EZMOTOR_H
#define ARDUINO_EZMOTOR_H

#if defined(ARDUINO) && ARDUINO >= 100
  #include "Arduino.h"
#else
  #include "WProgram.h"
#endif

/// Debug routine, emulates printf, limited to 127 chars.
void debug(char *fmt, ...);

//enum Direction { Backward = LOW, Forward = HIGH };

class Motor
{
public:
    Motor();
    void attach(int dir_pin0, int pwm_pin0);
        void attach(int dir_pin0, int dir_pin1, int pwm_pin0);
    void write(int speed);
    void flipDirection();
        void brake();
        void coast();

private:
    int dir_pin;
        int dir_pin2;
    int pwm_pin;
    boolean dir_HIGH;
};

#endif
```

local_ezmotor.cpp

```
#include "local_ezmotor.h"
#include <stdarg.h>

void debug(char *fmt, ...)
{
    char tmp[128];
    va_list args;
    va_start(args, fmt);
    vsnprintf(tmp, 128, fmt, args);
    va_end(args);
    Serial.print(tmp);
}


Motor::Motor()
{
    dir_pin   = -1;
    dir_pin2  = -1;
    pwm_pin   = -1;
    dir_HIGH = true;
}

void Motor::attach(int dir_pin0, int pwm_pin0)
{
    pinMode(dir_pin0, OUTPUT);
    pinMode(pwm_pin0, OUTPUT);
    dir_pin   = dir_pin0;
```

```
    pwm_pin = pwm_pin0;
}

void Motor::attach(int dir_pin0, int dir_pin1, int pwm_pin0)
{
    pinMode(dir_pin0, OUTPUT);
    pinMode(dir_pin1, OUTPUT);
    pinMode(pwm_pin0, OUTPUT);
    dir_pin   = dir_pin0;
    dir_pin2   = dir_pin1;
    pwm_pin = pwm_pin0;
}

void Motor::write(int speed)
{
        speed = constrain(speed,-255,255);
    if (speed < 0) {
        if (dir_HIGH) {
                digitalWrite(dir_pin, HIGH);
                if (dir_pin2 != -1) digitalWrite(dir_pin2, LOW);
        } else {
                digitalWrite(dir_pin, LOW);
                if (dir_pin2 != -1) digitalWrite(dir_pin2, HIGH);
        }
        analogWrite(pwm_pin, -speed);
    } else {
        if (dir_HIGH) {
                digitalWrite(dir_pin, LOW);
                if (dir_pin2 != -1) digitalWrite(dir_pin2, HIGH);
        } else {
                digitalWrite(dir_pin, HIGH);
                if (dir_pin2 != -1) digitalWrite(dir_pin2, LOW);
        }
        analogWrite(pwm_pin, speed);
        }
}

void Motor::flipDirection()
{
        dir_HIGH = !(dir_HIGH);
}

void Motor::brake()
{
        if (dir_pin2 != -1) {
                digitalWrite(dir_pin, HIGH);
                digitalWrite(dir_pin2, HIGH);
        } else {
                return; //"Error: Brake functionality not available for single direction input";
        }
}

void Motor::coast()
{
        analogWrite(pwm_pin, 0);
}
```

local DifferentialDrive.h

```
#ifndef DifferentialDrive_H
#define DifferentialDrive_H

#if defined(ARDUINO) && ARDUINO >= 100
  #include "Arduino.h"
#else
  #include "WProgram.h"
#endif

#include "local_ezmotor.h"
```

```
class DifferentialDrive
{
public:
    DifferentialDrive();
    void attachMotor(int dir1, int dir2, int pwm);
    void set_desired_heading(float h);
    void set_desired_velocity(int v);
    void update_motors();
    void set_current_heading(float h);
    void set_current_velocity(int v);
    float get_current_heading();
    float k_heading;
    float k_velocity;
    Motor left_motor, right_motor;

private:

        int num_motors_attached;
        float current_heading;
        float desired_heading;
        int current_velocity;
        int desired_velocity;
        int pwm_limit;
        int base_pwm;
        int left_pwm;
        int right_pwm;

};

#endif
```

<u>local DifferentialDrive.cpp</u>

```
//#include "ezmotor.h"
#include "local_DifferentialDrive.h"
#include <stdarg.h>

DifferentialDrive::DifferentialDrive()
{
    num_motors_attached = 0;
    current_heading = -1;
    desired_heading = -1;
    current_velocity = -1;
    desired_velocity = -1;
    pwm_limit = 255;
    base_pwm = 50;
    left_pwm = 0;
    right_pwm = 0;
    k_heading = 0.0;
    k_velocity = 0.0;
}

void DifferentialDrive::attachMotor(int dir_pin0, int dir_pin1, int pwm_pin0)
{
    if (num_motors_attached == 0) {
        // attach motor 1 (left motor)
        left_motor.attach(dir_pin0, dir_pin1, pwm_pin0);
      num_motors_attached++;
    } else if (num_motors_attached == 1) {
        // attach motor 2 (right motor)
        right_motor.attach(dir_pin0, dir_pin1, pwm_pin0);
    } else {
        //ERROR: You can only attach two motors to a differential drive robot.
    }
}

void DifferentialDrive::set_desired_heading(float h)
{
```

```
        desired_heading = h; // (in degrees with 90 = straight ahead)
}

void DifferentialDrive::set_desired_velocity(int v)
{
        desired_velocity = v;
}

void DifferentialDrive::set_current_heading(float h)
{
        current_heading = h; // (in degrees with 90 = straight ahead)
}

void DifferentialDrive::set_current_velocity(int v)
{
        current_velocity = v;
}


float DifferentialDrive::get_current_heading()
{
        return current_heading;
}

void DifferentialDrive::update_motors()
{
        // CONTROL LAWS GO HERE
        // e.g. ...
        float dTheta;
//      float dTheta = desired_heading - current_heading; // (in degrees)
        float diff1 = current_heading - desired_heading;
        float diff2 = current_heading - (360 - desired_heading);
        Serial.print(diff1);
        Serial.print(" ");
        Serial.print(diff2);
        Serial.print(" ");
        if (abs(diff1) <= abs(diff2)) {
          dTheta = -diff1;
        } else {
          dTheta = diff2;
        }
        int dV = desired_velocity - current_velocity; // (in cm/s)

        //base_pwm += k_velocity*dV;
        base_pwm = 220;
//      left_pwm += k_velocity*dV;
//      right_pwm += k_velocity*dV;         /// *************** <----- DON'T FORGET TO UNCOMMENT
//      left_pwm = 100;
//        right_pwm = 100;
        left_pwm = base_pwm + int(k_heading*dTheta);      // signs may need to be flipped
        right_pwm = base_pwm - int(k_heading*dTheta);

        base_pwm = constrain(base_pwm, 100, 200);
        left_pwm = constrain(left_pwm, 100, 255);
        right_pwm = constrain(right_pwm, 100, 255);

        Serial.print("DV: ");
        Serial.print(desired_velocity);
        Serial.print(" CV: ");
        Serial.print(current_velocity);
        Serial.print(" dV: ");
        Serial.print(dV);
        Serial.print(" CH: ");
        Serial.print(current_heading);
        Serial.print(" dTheta: ");
        Serial.print(dTheta);
        Serial.print(" LPWM: ");
        Serial.print(left_pwm);
        Serial.print(" RPWM: ");
```

```
        Serial.println(right_pwm);

        left_motor.write(left_pwm);
        right_motor.write(right_pwm);
}
```

fod_bot.pde

```
#include <TinyGPS.h>
#include "local_DifferentialDrive.h"
#include <NewSoftSerial.h>


DifferentialDrive fody; // heading gain, velocity gain
TinyGPS gps;
NewSoftSerial nss(11, A2);
const int enc1A = 2, enc1B = 12, enc2A = 3, enc2B = 13;
long left_odom, right_odom;
float TICKS_PER_CM = 21.145,
      TICKS_PER_DEGREE = 15.478;

struct waypoint {
  float x;
  float y;
};

float lat, lon, heading, velocity;
unsigned long age;
boolean newdata;

waypoint gps_waypoints[20];
int num_waypoints;

float last_heading;
float desired_heading;
int desired_velocity;

void setup() {
  Serial.begin(115200);
  nss.begin(4800);

  // attach motors
  fody.attachMotor(4,5,9);  // M1
  fody.attachMotor(8,7,10); // M2

  // set gains
  fody.k_heading = 1.0;
  fody.k_velocity = 1.0;

  // attach encoders
  attachInterrupt(0, read_quad_right, CHANGE);
  attachInterrupt(1, read_quad_left, CHANGE); // interrupt 1 conflicts with dir_1a

  initialize_waypoints();
  add_waypoint(42.40352, -71.11911); // 4 on track
  //add_waypoint(42.40602, -71.11690); //anderson hallway
  add_waypoint(42.40313, -71.11809);
  //add_waypoint(42.40334, -71.11775);
  //add_waypoint(42.40360, -71.11753);
//  fody.add_waypoint(x, y);
//  fody.add_waypoint(x, y);
//  fody.add_waypoint(x, y);
//  fody.add_waypoint(x, y);

  fody.left_motor.write(150);
  fody.right_motor.write(150);
  delay(3000);
}
```

```
// ******* MAIN LOOP *********
void loop() {
  newdata = false;
  unsigned long start = millis();
  // Every 5 seconds we print an update
  //while (millis() - start < 1000)
  //{
    if (feedgps()){

      newdata = true;
    }
  //}

  update_waypoint();
  //fody.set_desired_heading(0);
  //fody.set_desired_velocity(0);
  update_current_state();
  fody.update_motors();         /// *************** <------ DON'T FORGET TO UNCOMMENT THIS!
}


void update_current_state() {
  if (newdata) {
    // zero encoders

    gps.f_get_position(&lat,&lon,&age);
    fody.set_current_velocity(int(gps.f_speed_mps()*100));  //[cm/s]
    //fody.set_current_velocity(100); //TAKE THIS OUT
    //Serial.println(" ARE WE HERE?");
    if (int(gps.f_speed_mps()*100) > 10) {
        left_odom = 0;
        right_odom = 0;
        fody.set_current_heading(gps.f_course());  //[degrees]
        last_heading = gps.f_course();
     }

    Serial.print("lat: ");
    Serial.print(lat);
    Serial.print(" lon: ");
    Serial.print(lon);

    print_float(lat, TinyGPS::GPS_INVALID_F_ANGLE, 9, 5);
    print_float(lon, TinyGPS::GPS_INVALID_F_ANGLE, 10, 5);

    Serial.print(" vel: ");
    Serial.print(int(gps.f_speed_mps()*100),DEC);
    Serial.print(" course: ");
    Serial.println(gps.f_course());
  } //else {
      float h = last_heading + ((float)(left_odom - right_odom))/(float)TICKS_PER_DEGREE;
      h += 720;
      int num_fit = h/360;
      h = h - num_fit*360;
      fody.set_current_heading(h);
 // }

  // calculate desired heading
  desired_heading = gps.course_to(lat,lon,gps_waypoints[0].x,gps_waypoints[0].y);
  Serial.print("DH: ");
  Serial.print(desired_heading);
  fody.set_desired_heading(desired_heading);
}

void update_waypoint() {
  if (gps_waypoints[0].x == 0 && gps_waypoints[0].y == 0) {
    Serial.println("Messed up");
    // we've reached the end of the waypoint queue... STOP
    desired_velocity = 0;
```

```
    //fody.k_velocity = 0;
    //fody.k_heading = 0;
    // stop the program ?
    // add new waypoints ?
  } else {
    desired_velocity = 60; //[cm/s]
    //int dist = (int)pow(pow(gps_waypoints[0].x - lat,2) + pow(gps_waypoints[0].y - lon,2),0.5);
    int dist = gps.distance_between(gps_waypoints[0].x,gps_waypoints[0].y,lat,lon)*100; //[cm]
    //Serial.println(dist);
    if (abs(dist) < 500) {  // distance from waypoint to consider that we're there (16ft ~= 500cm)
      Serial.println("Removing Waypoint.");
      remove_waypoint();
    }
  }
  fody.set_desired_velocity(desired_velocity);
}

void initialize_waypoints() {
  for (int i = 0; i < (sizeof(gps_waypoints)/sizeof(waypoint)); i++) {
    gps_waypoints[i] = (waypoint){0, 0};
  }
}

void add_waypoint(float x, float y) {
  gps_waypoints[num_waypoints] = (waypoint){x, y};
  num_waypoints++;
}

void remove_waypoint() {
  for (int i = 0; i < (sizeof(gps_waypoints)/sizeof(waypoint))-1; i++) {
    gps_waypoints[i].x = gps_waypoints[i+1].x;
    gps_waypoints[i].y = gps_waypoints[i+1].y;
  }
  num_waypoints--;
}



void read_quad_left() {
  if (digitalRead(enc2A) != digitalRead(enc2B)) {
    left_odom++;
  } else {
    left_odom--;
  }
}

void read_quad_right() {
  if (digitalRead(enc1A) == digitalRead(enc1B)) {
    right_odom++;
  } else {
    right_odom--;
  }
}



boolean feedgps()
{
  while (nss.available())
  {
    if (gps.encode(nss.read()))
      return true;
  }
  return false;
}

static void print_float(float val, float invalid, int len, int prec)
{
  char sz[32];
```

```
  if (val == invalid)
  {
    strcpy(sz, "*******");
    sz[len] = 0;
        if (len > 0)
          sz[len-1] = ' ';
    for (int i=7; i<len; ++i)
        sz[i] = ' ';
    Serial.print(sz);
  }
  else
  {
    Serial.print(val, prec);
    int vi = abs((int)val);
    int flen = prec + (val < 0.0 ? 2 : 1);
    flen += vi >= 1000 ? 4 : vi >= 100 ? 3 : vi >= 10 ? 2 : 1;
    for (int i=flen; i<len; ++i)
      Serial.print(" ");
  }
  feedgps();
}
```