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A Systematic Review of Methods for Cleaning FOD on Runways

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Abstract.

Foreign objects (FOD) that can be found on runways represent a great danger for aircraft on take-off or landing; FOD cleaning systems for runways fulfill two basic tasks: "Detection" and "Cleaning"; which have been developed in different works and researches in the last years, generally treating both tasks as one. Over time, a great advance in detection systems was obtained, starting at first from the traditional method, commonly called "FOD Walk", employing visual inspection by human personnel, to the use of radars and cameras that employ complex detection algorithms. On the other hand, in the cleaning task, the progress is not the same, since in many airports and air bases around the world the inefficient FOD Walk is still used, however, in some places there are automated cleaning systems that become efficient, using robots or vehicles that clean the FOD. In this paper we will review all these methods, classifying them and analyzing their operation to show their advantages, disadvantages, the quality with which they perform the work, and the opportunities they offer when using a specific method. In the end, a discussion and conclusions are offered that will help future researchers on the subject.

Keywords: cleaning, detection, FOD walk, methods, runway

1. Introduction

An indispensable requirement for the safety of any type of aircraft during takeoff and landing is the cleaning of the runway. If there is any type of foreign object or FOD, the aircraft runs the risk of suffering an accident, causing economic losses and damage to the aircraft structure, ranging from blown tires to the complete destruction of the aircraft.

The detection and cleaning of foreign objects on runways has been for many years a task relegated to a visual inspection; the starting point to treat these activities with due seriousness came after the crash of Concorde flight 4590 in 2000 where more than 100 people died, investigations revealed that the accident was caused by an object on the runway, which broke

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away from the aircraft itself and blew out a tire, causing a chain of events that led to the tragedy [1]. To avoid further incidents like this, the task of removing foreign objects from runways before takeoff or landing was initiated.

The first system to clear these objects is what we now know as the "traditional way" or "FOD Walk", which consists of a large number of personnel, either workers or military, divided into different sections of the runway to perform a visual inspection to the entire surface, this inspection must be done at appropriate times and in a hurry if the environmental conditions are unfavorable, as with solar radiation that is harmful to health, in addition, being performed by humans the inspection is affected by various factors such as visibility, distraction and fatigue; These factors reduce the reliability of the system in the correct cleaning of the runway. Currently, there are many airports and air bases that still perform the FOD Walk procedure, but there are also many others that have already implemented automated detection systems and in some cases also cleaning systems.

In order to improve the reliability of runway cleaning, advances and research have been carried out where automatic detection systems have been developed for this type of objects using: radars [2-7, 23-31], cameras [8-14], robots [14,15] and even a combination of these; cleaning systems independent of detection [16], and cleaning systems based on the data provided by the detection systems [17] have also been developed.

The difference that exists between "runway cleaners" and "FOD cleaners"; the first ones abound in the market and their main function is to clean runways and roads to remove grease, oil, rubber or other elements that may affect traction between tires and asphalt, on the other hand, "FOD cleaners" are in charge of cleaning runways by removing foreign objects that represent a danger to the integrity of vehicles or aircraft [18].

In the following sections, a compilation and brief description of methods will be made based on the type of task for which they have been developed, the elements required to perform such task, and the advantages as well as disadvantages of all these methods. Section II will discuss the operation of all the systems in question in general, Section III will classify and analyze the cleaning systems based on the task they are intended for and the advantages and disadvantages

they offer, and finally, Section VI will present the discussion and conclusions reached by the research team, which will be very useful for further work.

2. Runway Cleaning System Operation

The Runway Cleaning Systems consist of a structure, which is almost invariable, by which it is ensured that, at the end of the procedure, the runway is clean and free of FOD on it. The first step is the detection of the objects, it is performed by many methods such as:

- Visual inspection.
- Radar systems.
- Location of cameras on the runway.

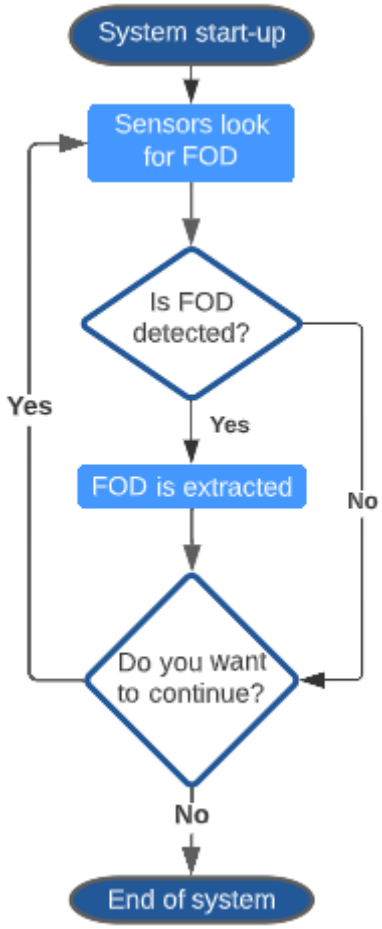
The main function of this step is to recognize and determine the position of the FOD on the runway to subsequently clean it, some of its additional functions are:

- Identify characteristics of the FOD: Determine its type, size, material, etc.
- Analize how these foreign objects arrived on the runway: By means of runway mapping, heat mapping and subsequent expertise.

The second and most important step, to the understanding of the research team, is the actual cleaning of the runway; there are also several methods to perform this task but the most common method is the manual one, that is to say that a person (or group of them through FOD Walk) is in charge of removing the FOD from the runway, recently automated cleaning methods have been developed that use robots that rely on detection systems to trace optimal routes and remove the FOD without human intervention; this whole process is summarized in the flow chart in Fig. 1.

In summary, the "FOD cleaning systems" are based on a dual system consisting of detection and cleaning activities, and in almost all cases it is impossible to separate them, i.e. there is usually no cleaning system that is not linked to a detection system.

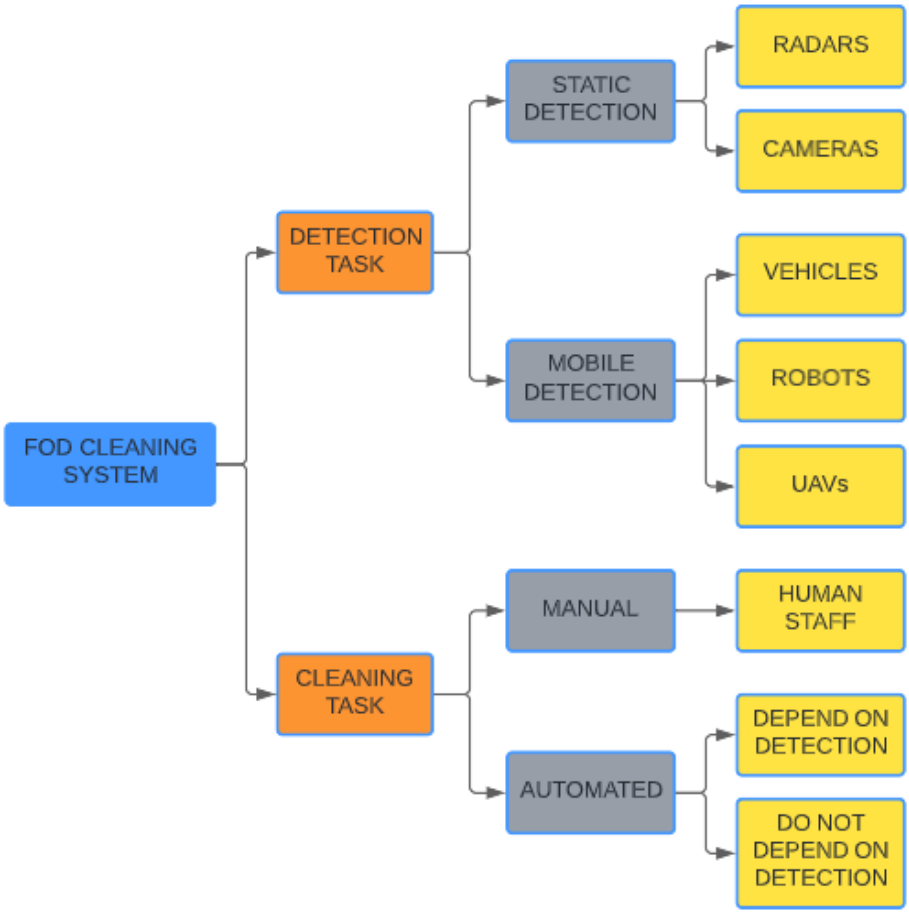
Figure 1: Principle of operation of the cleaning systems.



3. FOD cleaning system

Based on the literature of developments in different parts of the world, and on what was exposed in the previous point, it was observed that the FOD cleaning systems in runways are divided into two main tasks that must be carried out for the system to achieve its objective: The Detection Task and the Cleaning Task, as shown in Figure 2, which will be developed in the following.

Figure 2: Classification of the main tasks of FOD Cleaning Systems.



3.1 FOD Detection Task

The systems for the task of "Detection" are the ones that have had the greatest progress over the years. Due to the characteristics of the different advances, this task was divided into two main groups: "Static Detection Systems" and "Mobile Detection Systems".

3.1.1 Static Detection Systems

Static systems use cameras and radars that are fixed at one or several points on the runway, make use of image processing algorithms and/or improvements to the frequency, wavelength and electromagnetic noise filters on the radars. Projects in China used cameras and antennas on poles located at a certain distance from the runway [3]. Runway-side radars were also studied to detect distant FODs and found to have difficulty in trying to locate FODs because

they can be very small objects (6 cm^2) [19], to improve this, other projects focused on radars with varying frequencies to detect objects of different sizes [2], [4].

For the use of cameras instead of radars, work is being done to improve image processing using algorithms such as YOLO (You Only Look Once) to identify small FOD at long distances quickly [11], but the implementation and operation of these algorithms have high computational costs and radars and cameras have high economic costs because they require high quality in their performance, in addition the visibility of the cameras depends on the level of illumination in the area, limiting the work.

3.1.2 Mobile Detection Systems

Mobile Detection Systems are located in vehicles that travel along the runway detecting the location of the FOD, for these systems they work on image processing, with sensors and cameras; one research used UAS (Unmanned Aerial System) to detect FOD by flying over a fleet of UAVs at low altitude over the runways while mapping all detected objects [9], other methods developed in China, carried out two researches at the same time, one of these consists of a tele-operated robot equipped with laser sensors on the back [20], and the other research developed a detection system mounted on a vehicle that classifies objects by the possible damage they can cause to the aircraft, making it possible to focus the cleaning only on the FOD that represent a high danger, the cleaning of the FOD is developed at the same instant that it is detected because the vehicle can carry human personnel [8]. These systems also have a high computational cost because the algorithms must process too much information in real time and as the vehicles advance along the track; the cameras and sensors used must also be of the best possible quality to avoid errors due to the speed with which the processing is performed, which translates into a high economic cost.

- Advantages of the Detection task
  - They allow to recognize the FOD without the need of human personnel on the runway.
  - They allow to identify the shape, size and type of FOD, which allows to carry out surveys and investigations to determine the causes of the presence of such FOD on the runway.
  - Provides the possibility to perform statistics and mapping on the runway to determine which are the areas with the highest probability of FOD presence.
- Disadvantages of the Detection task
  - They require high economic and computational costs, due to the fact that in order to identify FOD accurately and quickly, image processing systems must be trained using deep learning methods and with equipment and software that have the appropriate performance for this purpose, in addition to the fact that static detection systems require even more investment in the infrastructure necessary to mount the radars and cameras.

- Cameras require good lighting, so it is somewhat problematic to perform these procedures at night or during certain weather conditions such as fog, heavy rain (which also hinders radar detection), desert areas with runways partially covered with sand and in hot places where solar reflection/refraction phenomena may occur and this could cause recognition errors.

3.2 FOD Cleaning Task

On the other hand, the Cleaning task has not had the same amount of research and therefore, the same development as the Detection task. In 2012, researchers from Tufts University, Boston developed a cleaning robot called FODHippo, which consists of squeegees and a small compartment to store a few FOD [10], later, in 2014, researchers from India developed Electric Walkway Cleaners, which consist of a sweeping system similar to the FODHippo but with the improvement of a rear suction system that absorbs all the swept material and takes it to a compartment, thus improving the cleaning quality [21]. In 2016, at the international airport of Istanbul, Turkey, tests were made for the automation of this task, creating a system that sends a swarm of FODHippo robots to collect the FODs according to an optimal route traced by an algorithm that uses the location points provided by the detection system used, in other words, the cleaning quality depended on the level of detection that could be given to the runway, this method is efficient, however, it is time consuming and the number of robots used is high, increasing the maintenance cost [14].

In 2020, in China, a vehicle mounted with different types of sensors and cameras was used to detect FOD quickly (this system was mentioned in the "Mobile Detection System" section), although this vehicle develops more the detection task it is also considered as an advance in the cleanup, because it can carry the personnel that will descend from the vehicle when it detects potentially dangerous FOD and clean them in the place where the FOD was located [8].

All these cleaning systems fulfill their purpose, but it is also clear that they are very dependent on the detection systems, which makes them unusable if the detection fails, in addition, by being automated they greatly increase the use of economic and computational resources and maintenance costs.

Finally, focusing only on the task of cleaning, it was observed that in a Russian aircraft carrier, empirically, the engineers in charge of runway maintenance mounted a MIG-15 aircraft engine on the front of a tractor to function as a blower and remove the FOD from the runway, this system proved to be efficient and fast, and also did not require prior detection [16]. Making a parallel with cleaning systems in other fields, we have that in industry one of the most used methods for cleaning surfaces is the "Cryogenic Cleaning System" which consists of compressed air blowers that drag dry ice particles to clean and disinfect various surfaces, it is mainly used in food industries, although also in the vehicle industry and in machinery, but to a lesser extent [5]. In everyday life, blowers are one of the best options to remove dirt and keep an area free of trash or any unwanted element, as in the cleaning of streets and green areas [22], the use of these types of cleaning systems, adapting to the required dimensions and with the

necessary power, could easily clean large areas efficiently as have seen in the aforementioned Russian aircraft carrier.

- Advantages of detection-dependent cleaning systems
  - In systems where human personnel are still used for cleaning, the pre-detection system represents a great saving of time and energy due to the fact that the person goes directly to the area with FOD and no longer needs to walk looking towards the track to find the FOD.
  - In automated systems, human intervention is no longer required.
  - These systems allow the collection of the FOD; therefore, an investigation can be made on each of the FOD found and determine where they belong and how they arrived at the area of the track where they were found.
- Disadvantages of the detection-dependent cleaning systems
  - In many of these systems, human personnel are still used to perform the cleaning task.
  - In the automatic systems, although humans are no longer required, a greater consumption of economic and computational resources is required, since the robots that are in charge of collecting the FOD are expensive, and when using swarms of these, the price rises too high, on the other hand, the optimal route tracing is performed by an artificial intelligence that is added to the image processing systems of the detection systems, making the performance of equipment and software even more complex.
  - The biggest disadvantage of these cleaning systems is that they are vitally dependent on the detection systems, i.e., if the previous detection system fails or has errors the whole cleaning system will be compromised and the track will not be cleared properly.
- Advantages of cleaning systems that do not depend on detection systems
  - Installation or start-up costs may be higher because the equipment must be more robust and powerful, but this additional cost is recovered by the savings in radar or camera infrastructure and computer costs, because no software is required for FOD identification or routing.
  - By not depending on any detection, these systems are not linked, so if detection fails or is not performed correctly, the cleaning system will continue to function, even in the weather conditions mentioned in previous points.
  - They can be used at any time of the day and under any conditions, in cases where the runway needs to be cleaned for an emergency situation.
- Disadvantages of cleaning systems that do not depend on detection systems

- The cleaning they provide is massive, i.e., they do not focus on collecting each FOD one by one, they collect or clear everything they find in their path, which makes it difficult to identify and later investigate the origin of the FOD that were on the runway.
- They are very powerful and relatively large systems, so if they are not properly designed and used, they can cause damage to previously damaged runways.
- They can be dangerous because they throw dust particles or FOD at high speed, so no person should be near the area where the cleaner is operating.

In Figure 3. the last ones are the ones that offer the best results, but, in the opinion of the research team, the cleaning task has a much higher value than the detection, so although the research that combines the detection with the swarm of robots FODHippo [14] is the most complete, it also uses more resources, so we consider that the blower method used in the Russian aircraft carrier [16] is the one that meets the objective in the same way as the previous one but with fewer resources, and it can even operate in unfavourable conditions, since it does not depend on the detection system, as mentioned in the advantages of cleaning systems that do not depend on detection.

Figure 3: Comparison of characteristics and reliability of detection-cleaning systems.

Detection	Cleaning	Mapping information	Use of resources	Detection reliability	Cleaning reliability
Visual (FOD WALK)	Manual (FOD WALK)	NO	LOW	LOW	LOW
Radar	NO	YES	MIDDLE	HIGH	-
Radar	Robots	YES	HIGH	HIGH	HIGH
Sensor Lidar	NO	YES	MIDDLE	HIGH	-
Camera	NO	YES	MIDDLE	HIGH	-
Drones (Camera)	NO	YES	HIGH	HIGH	-
NO	Russian Cleaner	NO	MIDDLE	-	HIGH

4. Discussion and Conclusion

Runway cleaning procedures consist of two main tasks, the detection task and the cleaning task. These tasks are summarized in Figure 4.

Research based on detection and runway cleaning systems performed in recent years was analyzed and it was noted that the most developed ones are those focused on the detection task, subdividing these systems (by the research team) into static detection and mobile detection.

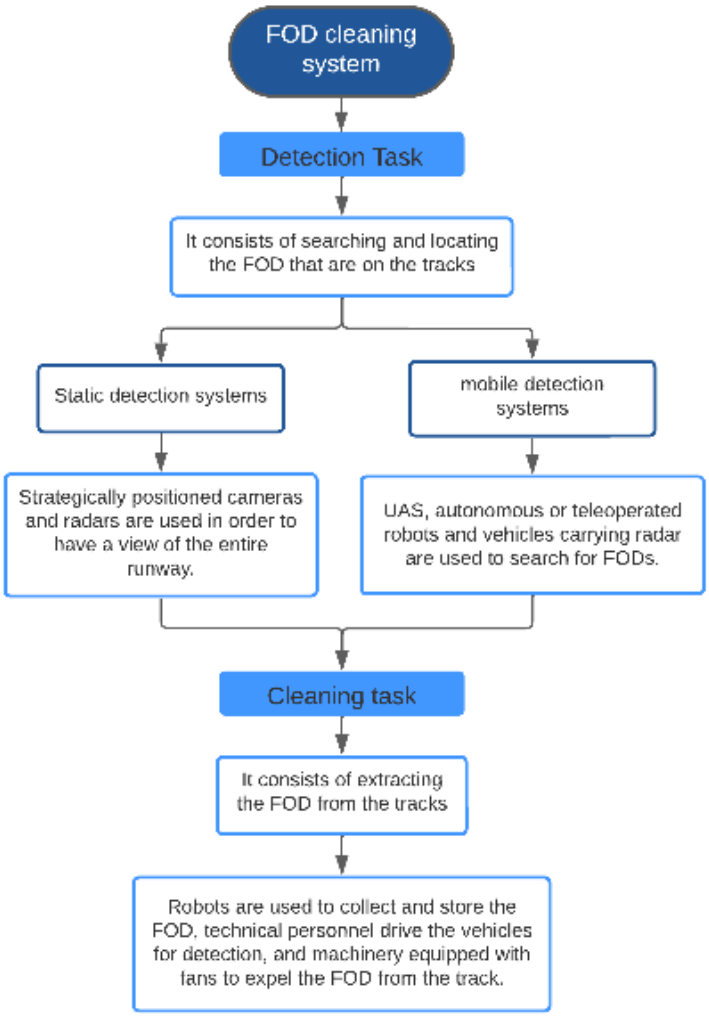
The methods to develop the detection task offer the ability to investigate the FOD found and take action to prevent further occurrence, however one of the main disadvantages is that for a proper inspection of the track must have adequate environmental conditions, since not having them the data provided could be erroneous and compromise the entire cleaning system, another disadvantage is that these automatic detection systems require a large computational expense and therefore a large economic investment.

On the other hand, cleaning systems have not had as much development nor are they as widespread as detection systems; in fact, in many places it is human personnel who perform this task regardless of the system used to detect FOD.

The main disadvantage of automated cleaning systems is that they are vitally dependent on some detection system, i.e., if the detection system fails for any of the reasons mentioned above, the cleaning system will be rendered useless.

Cleaning systems that do not require detection are the most suitable to ensure complete runway cleaning, being their main advantage that they do not need to be linked to any detection system, which allows them to operate under any environmental condition, on the contrary, their main disadvantage is that they do not provide the ability to perform subsequent investigations in the FOD which means that it will not be possible to map the areas of greatest presence of foreign objects and investigate how they reached the runway, however for emergency cleanings, this disadvantage becomes a secondary issue.

Figure 4: FOD Cleaning System Tasks.



This systematic review of FOD cleanup systems in general and research conducted in the field provided the research team with a better understanding of the subject and will allow better decisions to be made in future work on this research topic, highlighting the following points:

- Detection systems using cameras or radars allow to perform investigations on runways to prevent new FOD from reaching them, however they are high cost and lose reliability in adverse environmental conditions.
- Automated cleaning systems are dependent on detection systems and can be highly reliable or become unusable if detection is inadequate.
- Cleanup systems that do not rely on detection are massive, ideal for emergency cleanups but without the ability to map the track or collect FOD for further analysis.

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