3D Laser-based Fully Automated FOD Detection and Airfield Pavement Condition Inspection System

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Abstract: Over a decade ago, the infamous Concorde was downed by a small strip of metal just a few millimeters high. The Concorde’s tires ruptured upon strike of the Foreign Object Debris (or “FOD”), sending shrapnel flying into the fuel tank and causing it to explode.

At present, FOD remains a critical issue in the industry both from a safety standpoint as well as financially; with estimates of the annual worldwide cost pegged at a staggering US$13 billion.¹

Part of the challenge in the industry is that traditional manual inspection methods can miss upwards of 96% of the FOD present on airport surfaces due to its small size, location, and the practical limitations of even the best inspectors spotting debris while traveling at highway speeds.²

Significant advances in high-speed 3D imaging technology have been made in the last decade and there are now commercial off-the-shelf solutions for detecting FOD and evaluating pavement serviceability. This technology offers numerous advantages to the traditional manual survey method including:

- Improved safety to staff,
- Day or night-time operation,
- Improved speed of operation,
- Improved accuracy and reliability of results,
- Ability to detect much smaller FOD (as small as a few millimeters).

This paper describes this technology and its practical application in the field.

INTRODUCTION

Foreign Object Debris (FOD) is a critical issue in the industry both from a safety standpoint as well as financially; with annual worldwide cost estimated to be US$13 billion.

Traditional approaches to FOD detection involve the use of manual driving surveys wherein a single inspector, or sometimes a team of two, drives an inspection vehicle down the center of the runway at speeds typically ranging from 80-100 km/h and visually scans the surface for FOD.

However, research has shown that this approach misses upwards of 96% of FOD actually present on the runway. It’s not a surprising statistic given the challenge of an inspector spotting FOD across the large
surface area of a runway (runways being typically 50m wide) at high-speeds, under all lighting conditions.

The Laser Foreign Object Debris Detector (LFOD) can replace, or augment, the use of manual inspections with two or more high performance 3D laser profilers that are able to capture 1mm resolution 3D scans of airfield surfaces at speeds up to 100 km/h (65 mph). Each pair of sensors can scan a width of 6m and up to three pairs can be used simultaneously for a maximum scanning width of 18m.

![Figure 2 – LFOD Installed on an Inspection Vehicle](image)

The LFOD captures both 2D “Intensity” images as well as 3D (Range) data simultaneously which are processed in real-time using algorithms that automatically detect the presence of FOD (Figure 3) and extract related data such as:

- FOD location (linear reference and/or GPS coordinates),
- FOD height (max, min, average),
- FOD area.

![Figure 3 – Results of Automatic FOD Detection](image)
HARDWARE CONFIGURATION
The LFOD system consists of 2 or more 3D laser profilers mounted on the rear of a standard inspection vehicle, high-speed industrial computers and sophisticated image processing algorithms.

The LFOD’s 3D laser profilers use high power laser line projectors, custom filters and a camera as the detector (Figure 4). The laser is projected onto the pavement surface and its image is captured by the camera.

A high-resolution optical encoder is used as an odometer to synchronize sensor acquisition as the inspection vehicle travels across the airfield surface. Images from the cameras are digitized by high-speed frame grabbers and then processed in real-time by the CPU. Images are compressed to 1/40th of their raw size using lossless data compression algorithms to minimize data storage requirements.

![Figure 4 - LFOD Sensors](image)

The LFOD sensors simultaneously acquire both 3D “Range” and “Intensity” images of the scanned surfaces. Automatic algorithms are used to analyze each data stream in order to extract different data elements; for example, the presence of pavement markings can be detected from intensity images and the presence of FOD or pavement cracking can be detected from range data.

INTENSITY DATA
Intensity profiles provided by the LFOD are used to form a continuous image of the scanned surface. Intensity images can be used to identify the type of FOD present on airfield surfaces; Figure 5 illustrates the intensity image for a number of different kinds of FOD.
Intensity images can also be used to detect highly reflective painted surfaces such as pavement striping and informational messages as such markings are highly contrasted compared to the surrounding pavement. With the proper pattern recognition algorithms, various markings can be identified and surveyed.

**3D RANGE DATA**

The 3D data acquired by the LFOD system measures the distance from the sensor to the surface for every sampled point on the road. Figure 6 shows a range data image acquired by the sensors. In this image, elevation has been converted to a gray scale.

In the range images, the lighter the point, the higher the surface is; so features sitting on top of the airfield (FOD) appear light grey or white in range images whereas features whose depth extends beneath the top surface of the runway (e.g., cracks, raveling, rutting, potholes, etc.) appear as dark grey or black in colour.

In range images, FOD are readily visible with the naked eye (Figure 7), although FOD detection is actually
performed using automated algorithms which analyze the 3D data in real-time (100 km/h) and apply minimum criteria for detection.

From a pavement condition inspection perspective, most features are located in the high-spatial frequency portion of the range data. Figure 8 shows a 2 meter wide transverse profile where the general depression of the profile corresponds to the presence of a rut, the sharp drop in the center of the profile corresponds to a crack and the height variations around the red line correspond to the macro-texture of the airfield surface.

**REALTIME FOD DETECTION**

As the inspection vehicle is being driven, and the LFOD sensor is scanning the airfield surface, 3D data scans are transferred via a high-speed network connection to an onboard processing computer. FOD detection algorithms scan the 3D profiles for presence of debris which exceed operator-specified thresholds for minimum height and area. Features meeting the minimum height and area criteria are recorded as FOD and their position as well as height, area and an actual image of the object are recorded for each (Figure 9).
A “severity rating” can be given to each detected FOD based upon its height and area with the operator being able to configure the height and area ranges according to 3 levels of severity: high, medium and low (Figure 10). High severity FOD are marked in images using a red color, Medium severity are marked using an orange colour and Low severity FOD are marked using a green colour.

Audio alarms can be set by the operator to trigger only upon the detection of FOD of a minimum height and area. This is particularly useful considering the high sensitivity of the system and its ability to detect FOD down to a size of a few millimetres. The GPS coordinates, dimensions and images of small FOD which do not meet the airport-set criteria for immediate retrieval can be stored and used to create a targeted work program for weekly runway sweeping or vacuuming.
SCANNING PROCEDURE

The LFOD system can be deployed in a number of ways depending on the operational needs of the user. During peak hours, when the time between take-offs and landings is at a minimum, the system can be operated in a single pass mode with the inspector following the same survey route as they normally would for a visual survey. In this way the inspector can concentrate on visually scanning the surface of the runway at its edges for the presence of FOD while the LFOD scans the middle portion of the runway using its high-speed lasers and automated algorithms.

This approach provides excellent coverage (up to 18m) of the center of the runway for small debris which could result in a wheel strike (as was the case in the Concorde accident). Importantly, the 18m scanning width also ensures coverage of the critical landing gear footprint of the Boeing 747-8 Code F and Boeing 747-400 Code E as depicted in Figure 11:

![Figure 11 - Boeing 747-8 and 747-400 Main Gear Span](image)

During off-hours (e.g., at night-time during no fly times), the LFOD can be used to quickly perform an extremely detailed FOD survey that would be practically impossible to perform using visual methods due to lighting conditions. In these situations the inspector can scan the runway surface using just a few passes to ensure 100% coverage at 1mm scanning resolution.

Using a combination of approaches; single-pass scans during peak times, and detailed scans in off-hours, the LFOD can contribute significantly to an airport’s runway safety through the efficient detection of FOD.
FOD REPORTS
A number of different data elements are available as outputs from the system so as to allow the user to better manage their risk due to FOD. For each detected FOD the system records the following:

- FOD location (linear as well as latitude, longitude and elevation),
- FOD height (max, min and average),
- FOD area,
- Images of the FOD (range, intensity and 3D),
- FOD “severity rating” (High, Medium, Low).

Data are stored in an XML data format which can be readily imported into a variety of database and/or file formats such as Microsoft Access, Microsoft SQL, Oracle, Microsoft Excel, etc.

Additionally, a report can be generated using Google Earth (Figure 12) such that the locations of detected FOD are highlighted on a satellite or aerial photo in Google along with a data file for each item detailing the FOD’s key characteristics.

Over time, a database of detected FOD can be created documenting the date and time, locations, sizes and types of FOD detected at the airport. This information can serve as a valuable input into an airport’s Safety Management System.
APPLICATIONS OF DATA FOR PAVEMENT MANAGEMENT

One of the unique features of the LFOD system is its dual-purpose nature; the high-resolution 3D scans which it captures can also be processed by algorithms which will automatically determine the condition of the runway surfaces. These data items can be used to support a full pavement management program for an airport’s paved surfaces using MicroPAVER™ or other Pavement Management System software applications.

Figure 13 - Pavement Deterioration Curve

Algorithms for the detection and quantification of a wide range of pavement distresses are available including:

- Longitudinal profile and/or roughness
- Transverse profile and rutting
- Potholes
- Longitudinal cracking
- Transverse cracking
- Pattern cracking
- Crack and/or joint seal failure
- Concrete slab faulting
- Macrotecture
- Bleeding
- Raveling
Automatic Crack Detection and Width Measurement

Lost Aggregate (Raveling) Detection and Quantification

Joint Fault Detection and Quantification

Longitudinal Profiling and Roughness Reporting

Macrotexture Measurement

Bleeding and Rubber Contamination Detection

Figure 14 - Automatic Pavement Condition Analysis Algorithms
COMPARISON TO OTHER FOD DETECTION METHODOLOGIES

Although standard visual inspection for FOD detection and pavement condition rating is still very much the norm in the industry, there have been some recent technological entrants in the marketplace.

However, in comparison to even the most sensitive competing solutions, the LFOD is able to detect FOD 1/10\textsuperscript{th} of the size for 1/10\textsuperscript{th} of the cost and is also deliver a complete and fully automated pavement condition rating solution. A comparison of available technologies is presented in Table 1.

<table>
<thead>
<tr>
<th>FOD Detection Technology</th>
<th>FOD Sensitivity</th>
<th>Description</th>
<th>Stationary/Mobile</th>
<th>Ability to Rate Pavement</th>
<th>Market Price*</th>
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<tbody>
<tr>
<td>High mast mounted cameras</td>
<td>Daytime &gt;40 mm.</td>
<td>Optical-based FOD detection.</td>
<td>Stationary; must install at each area to scan (e.g., each runway, taxiway, etc.).</td>
<td>No</td>
<td>~$14,000,000US per runway.</td>
</tr>
<tr>
<td>Combined runway-level near infrared cameras and stationary radar</td>
<td>Daytime &gt;25mm. Night-time &gt;50mm. Limited ability to detect some materials.</td>
<td>Radar and optical-based FOD detection. Runway-mounted sensors are at risk during ground operations such as snow clearing.</td>
<td>Stationary; must install at each area to scan (e.g., each runway, taxiway, etc.).</td>
<td>No</td>
<td>~$4,000,000US+ per runway.</td>
</tr>
<tr>
<td>Combined mobile radar and stationary radar</td>
<td>Mobile &gt;200mm. Stationary &gt;50mm. Limited ability to detect some materials.</td>
<td>Radar-based FOD detection.</td>
<td>Hybrid.</td>
<td>No</td>
<td>~$10,000,000US per runway and ~$400,000US per vehicle.</td>
</tr>
<tr>
<td>Combined stationary radar and high mast mounted cameras</td>
<td>Daytime &gt;20mm. Night-time &gt;2500mm. Limited ability to detect some materials.</td>
<td>Radar and optical-based FOD detection.</td>
<td>Stationary; must install at each area to scan (e.g., each runway, taxiway, etc.).</td>
<td>No</td>
<td>~$18,000,000US per runway.</td>
</tr>
<tr>
<td>Pavemetrics LFOD</td>
<td>Daytime &gt;1mm. Night-time &gt;1mm. Can detect any material.</td>
<td>Laser-based, 3D detection of FOD at speeds up to 100 km/h.</td>
<td>Mobile; can cover all airport surfaces.</td>
<td>Yes</td>
<td>~$750,000US for entire facility.</td>
</tr>
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</table>

*Market Prices have been obtained through publicly available procurement records for the purchase of FOD detection systems.

Table 1- LFOD Comparison with Other Methodologies
CONCLUSIONS

FOD remains a critical issue in the industry both from a safety standpoint as well as financially; estimates of the annual worldwide cost are US$13 billion. However, present industry practices rely on visual inspection which can miss upwards of 96% of FOD present on airport surfaces due to their size, location and the practical challenge of spotting FOD at highway speeds.

The LFOD can significantly reduce an airport’s exposure to FOD risk and provides the added benefit of being able to automatically determine pavement condition for pavement management purposes.

REFERENCES

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i Runway Safety: FOD, Birds, and the Case for Automated Scanning, Insight SRI, 2010
ii Runway Safety: FOD, Birds, and the Case for Automated Scanning, Insight SRI, 2010