

Design of an Enhanced FOD Inspection System for the Aircraft Assembly Process

Justin Amoyal, Roman Garber, Marwan Karama, Meba Kassahun and Anoosha Koohi
George Mason University, @gmu.edu

Abstract – Foreign object debris is any object alien to an aircraft assembly component, examples include screws, fasteners, bottle caps, tools, and trash. Currently, visual inspection techniques are used to detect FOD. These methods, relying on line-of-sight, are time consuming (5-10% shift time), costly (\$13B direct costs annually) and subject to errors (i.e. 50% FOD remains undetected after inspection). Analysis of production data shows that a typical fighter jet production line with 26 assembly stations will experience one FOD event on average every 5.46 hours.

An enhanced FOD detection system (FODXSYS) proposed combines X-ray imaging technology with differential imaging software. This system aims to improve efficiency and decrease production costs.

A discrete event simulator [FODSIM] was developed to estimate the effect of FOD on aircraft production time, cost, and quality. There are 26 assembly processes modeled station-by-station. Historical FOD data was used to derive an inter-arrival time of FOD occurrences [Exponential ($\lambda=0.0102$ hours)], and FOD rework times [Exponential ($\lambda=9.51$ hours)].

Analysis of FODSIM output indicates a savings of \$8M; 5 years post implementation, and \$18M after 10 years. A break-even analysis shows that an initial investment of \$2M for 5 X-ray machines requires 5.5 years to reach a break-even point.

Keywords- Foreign Object Debris, FOD, Aircraft Manufacturing, Discrete Event Simulation, X-Ray Imaging

INTRODUCTION

Fighter jet assembly is a complex and expensive process, requiring thousands of parts, tools, and other equipment from a variety of manufacturers to make it all possible. The F-35, requiring more than 300,000 individual parts from 1,400 suppliers was selected as the case model for this project [1].

Losing or misplacing any of these individual parts, or tools required can have significant effects on assembly. Leaving behind any item, even a screw presents the potential for many disruptions within assembly time, cost and quality as a result of the associated dangers of this item interfering with any moving parts within the aircraft post assembly.

Any items that could be lost, misplaced, or forgotten are defined as Foreign Object Debris [FOD], this includes tools, sub-assembly components, and even trash. Current FOD arrival rates are as follows - panstock (33.6%), consumables (13.71%), manufacturing debris (19.09%), tools/shop aids (8.74%), and trash (24.87%) [2]. A typical fighter jet production line with 26 assembly stations is estimated to experience one FOD event approximately every 5.46 hours.

Throughout each shift personnel on the production line are required to perform FOD searches, 5-10% of total shift time is the time estimated for these manual inspections, which are limited to an average of 50% search success rate [2]. These manual inspections are represented by the magnifying glasses displayed in Figure 1. The type II error resulting from the probability of a successful inspection is a compounding error, as the assembly component advances through production it becomes increasingly more difficult to detect as a result of the additional components mated to the initial one where the item was lost.

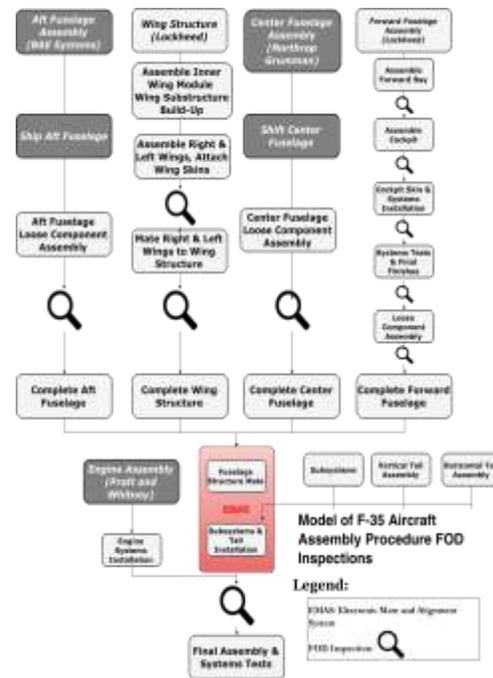


FIGURE 1
AIRCRAFT ASSEMBLY FLOW WITH MANUAL INSPECTION

Although there is a non-linear relationship between FOD occurrences and cost; there is a linear relationship between the point in production an aircraft has reached and the FOD associated costs; the threshold is the Electrical Mate and Alignment Station [EMAS], which is highlighted in red in Figure 2, where the 3 initial fuselage components (Aft, Center, Forward) and the Wing Module are mated.

STAKEHOLDERS

I. AC Manufacturers

- **Objectives:** Assemble and Manufacture fighter jets, as efficiently and cost effective as possible with the absence of FOD.
- **Tension:** Manual Inspection methods require high labor costs for production line personnel and FOD inspectors.

II. FOD Inspectors/Production Line Personnel

- **Objectives:** Inspect and detect 100% FOD present in assembly components throughout the aircraft assembly process while completing the tasks required per shift.
- **Tension:** Humans are limited to top layer visibility, and therefore cannot detect any FOD beneath the surface. FOD inspections take time and focus from production line personnel that could be better utilized.

III. AC Customers

- **Objectives:** Purchase fighter jets free of FOD, for the best price and on time.
- **Tension:** Deadlines could be extended as a result of an unexpected FOD occurrence requiring high rework and repair hours.

PROBLEM AND NEED

I. Problem

The 50% probability of a successful manual FOD inspection has contributed to the \$13 billion annually attributed to FOD damage [3]. Since humans carry out the manual inspection at each station, line of sight is relied upon. Within each inspection there is a high potential for human error as a result of distractions, fatigue, and bias. After conducting the same inspection daily, humans become accustomed to applying higher focus to areas where they expect to find FOD and therefore less into the other areas. FOD occurrences also affect the customer, unexpected rework and repair hours delay the assembly process therefore postponing deadlines.

TABLE I
PROBLEMS AND GOALS ACCORDING TO PRIORITY

PRIORITY	MANUAL FOD INSPECTION	ENHANCED INSPECTION SYSTEM
INSPECTION CAPABILITIES	LINE OF SIGHT (TOP LAYER)	MULTILAYER VISIBILITY
HUMAN ERROR	HIGH POTENTIAL	DECREASE
TIME	INEFFICIENT	DECREASE
DETECTION LOCATION	LATE	EARLY

II. Need

There is a need to optimize the way in which FOD is detected during Aircraft assembly. Specifically, decreasing the total hours devoted to inspections and rework hours required per aircraft assembled. An Enhanced FOD inspection system provides the opportunity for inspections in fractions of the time, with a higher probability of detection at each, limiting the total number of inspection stations, rework required per aircraft, ultimately increasing the total number of aircraft that can be assembled per year.

CONCEPT OF OPERATIONS

I. Concept of Operations

An enhanced FOD Detection system (FODXSYS) proposed combines X-ray imaging technology enabling a multi-layer view, with differential imaging software to assist the operator with detection recommendations.

The proposed system would use an enhanced FOD detection system at critical points in the assembly process, which lie immediately before the mating point, EMAS, as displayed in Figure 2.

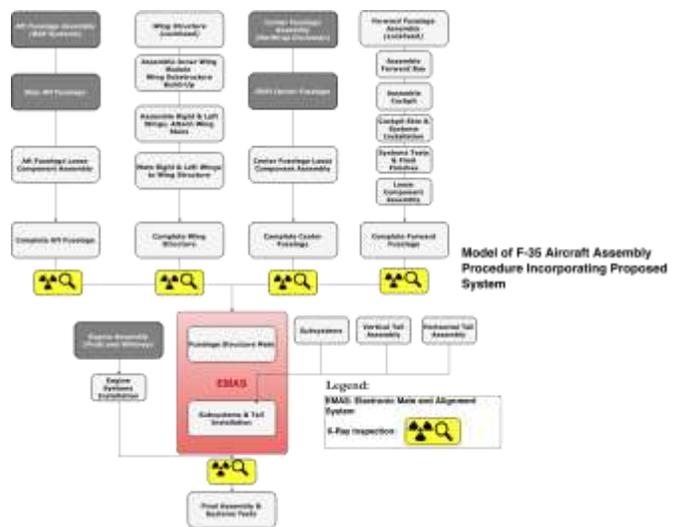


FIGURE 2
AIRCRAFT ASSEMBLY FLOW WITH FODXSYS INSPECTION

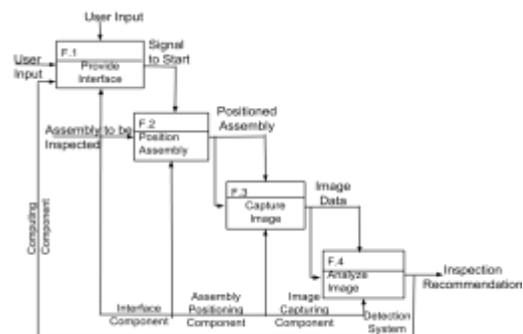


FIGURE 3
IDEF.0 OF FODXSYS F.0 INSPECT FOR FOD

The IDEF.0 diagram depicts the interaction between the system’s sub functions in order to produce the final output, an inspection recommendation. Signals are sent to trigger the sub functions as well as the dependent inputs that come from the preceding functions. This diagram also shows the physical and allocated architectures for the systems functions, by depicting the sub-system responsible for performing each of the sub functions.

II. System Requirements

With assistance from the project sponsor, the requirements displayed below in Table II were derived for the enhanced inspection system.

TABLE II
SYSTEM REQUIREMENTS

MR.#	Requirement Description
MR.1.0	System shall have a 95% FOD detection rate in all portions of the Aircraft
MR.2.0	System shall support a production rate of 1 plane/day
MR.3.0	On-site support shall be provided for 2 weeks per installation location during initial operational phase of equipment.
MR.4.0	Supplier shall provide 1 week of operator training for 10 operators
MR.5.0	System shall have an ROI of 25% based on LM data sample acquired before the integration of the system and data sample acquired approximately 12 months after system integration
MR.6.0	System shall reduce FOD inspection times by 50% based on LM data sample acquired before the integration of the system and data sample acquired approximately 12 months after system integration.
MR.7.0	Supplier shall develop an integration plan for incorporation of the equipment into the F-35 production plan. Plan shall be approved by LM 30 days prior to installation.

DESIGN ALTERNATIVES AND SYSTEM VALIDATION

I. X-ray Alternatives

There are three components: X-ray, Mounting and Differential Imaging. Based on the primary materials, and thicknesses associated with the sub assembly components inspected at each station a minimum input voltage (220 kilo Volts) was determined, to establish it was possible to scan and detect with 95% accuracy within these components. Different mounting alternatives were considered for the critical inspection locations.

TABLE III
X-RAY ALTERNATIVES

Wing Inspection Station	Average Cost (\$)	Accessibility	Average Power Req. (watts)	SNR (Aluminum, Wing)	SNR (Carbon, Wing)	Penetration Depth through Steel (mm)	Start Up Time (min)	Scan Speed (m/s*2)
X-ray Mounting Alternative								
Weight		.23	.21	.11	.08	.06	.09	.22
Preference	Low	High	Low	High	High	High	Low	Low
Linear Rail	272,000	.28	650	2.39	3.38	6.3	20	0.185
Robotic Arm	301,000	.50	650	2.39	3.38	6.3	20	0.185
Gantry	200,000	.11	620	2.39	3.38	400	15	9.6
Z-Portal	200,000	.11	480	2.39	3.38	300	15	9.6

II. System Validation

The ability to detect a FOD inside an aircraft component during inspection is directly related to the ratio of the x-ray intensity through the specific material of component to the background or object noise level. This ratio is called the absolute contrast to noise ratio, or the image signal to noise ratio. In general, noise is the main limiting factor in the ability to detect the object and being imaged with an x –ray device, especially when viewing objects with small and low-contrast.

$$\text{Signal to Noise Ratio} = (I_s)_{\text{mean}}/\sigma \quad (1)$$

The mean intensity and SNR equations were utilized to verify the ability of the X-ray alternatives considered to penetrate through the assembly components at each inspection station and output a clear image. Exact dimensions on the F-35 components are proprietary so estimations were calculated based on scaled models. Using a total height of 14.3 ft [4], the fuselage was estimated at 1.64 feet, and wing module at 0.83 feet. The height of the different component is considered as the distance that the x-ray beam should travel.

The primary materials used in fuselages and wing modulus are carbon and aluminum which have linear attenuation coefficients equal to 0.02 and 0.05[5]. The SNR obtained for aluminum and carbon portions of the fuselage and wing module are higher than 1, which represents an accuracy equivalent to 95% probability of detection.

III. X-ray Mounting Alternatives Decision Analysis

Figure 4 displays the weights determined for each of the attributes of the X-ray mounting alternatives, which were determined by utilizing the swing weights method. Utility vs Cost analysis was conducted in order to select the optimal X-ray mounting alternative – Robotic Arm System. With the second lowest cost (\$301,000) and the highest Utility score (.67) of all alternatives, it was a clear decision.

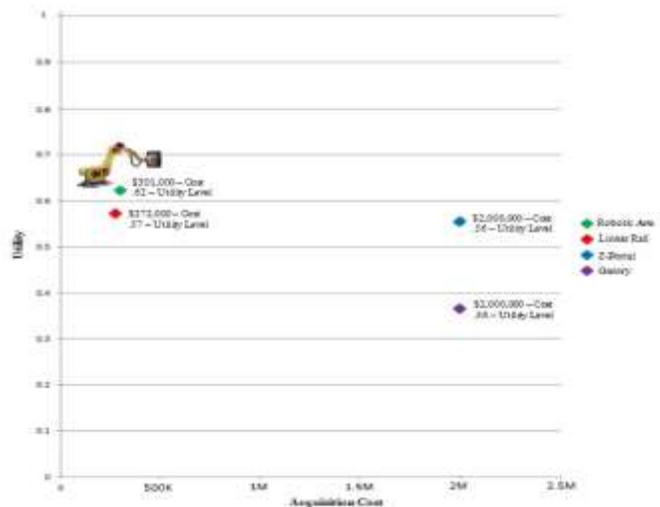


FIGURE 4
X-RAY MOUNTING ALTERNATIVES

Rate and Rework Time were then minimally adjusted until FODSIM output data was within three standard deviations of the historical data.

RESULTS

Results were obtained by running FODSIM for 1000 one-year-long iterations under both manual inspection and FODXSYS. Results on rework and repair hours, total aircraft out, number of aircraft with FOD present at end of production, and the total inspection hours. Analysis was then conducted using both a t-test and a non-parametric test to establish the robustness of the data towards drawing conclusions.

I. Total Rework and Repair Hours

Summing the total rework and repair performed by each station and dividing by the total of number stations outputted an average number of rework and repair hours for each iteration. A comparison of total repair hours is shown in the histogram in Figure 7, the distributions between the manual and FODXSYS over the 1000 runs.

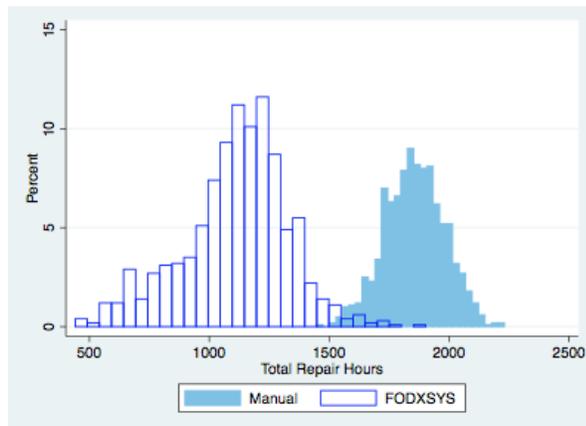


FIGURE 7
DISTRIBUTION - TOTAL REPAIR

FODSIM indicates that the implementation of FODXSYS will decrease the average rework and repair being performed each year by 40%. This is due to the fact that FODXSYS guarantees that no FOD occurrence prior to E-MAS reaches EMAS, eliminating the more severe cases of FOD where the Aircraft must be disassembled.

II. Total Inspection Labor Hours

By eliminating the repeated inspections after each station, FODXSYS dramatically reduces the total inspection hours per year in comparison to the manual process, total inspection hours for FODXSYS averaged to 212 hours/year, while total manual inspection hours 2811 hours/year.

III. Average Difference of Aircraft Assembled

A t-test provided significant enough results to reject the null hypothesis, which stated the mean number of aircraft produced with Manual and FODXSYS would be equal. With

95% Confidence it can be estimated that between 5 and 6 more aircrafts will be produced per yearlong iteration with FODXSYS.

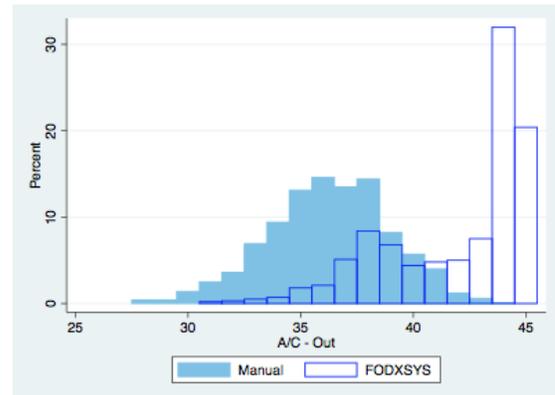


FIGURE 8
DISTRIBUTION - TOTAL # OF AIRCRAFT ASSEMBLED/YEAR

This statistic relates directly to potential profit for an Aircraft Manufacturer. The increase in average number of aircrafts produced per year is a result of the decrease in average hours required per aircraft.

IV. Quality

The reputation of the Aircraft manufacturer and the safety of the Aircraft operators are dependent on the delivery of FOD-free Aircraft. FODXSYS successfully manages to reduce the yearly number of aircrafts delivered with FOD.

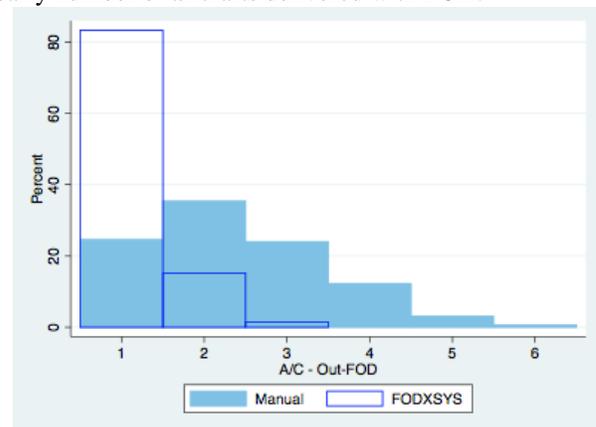


FIGURE 9
DISTRIBUTION - AIRCRAFT COMPLETED WITH FOD REMAINING

V. Total Labor Hours per Aircraft

By adding the standard labor, inspection labor and rework labor, the Total hours of labor are calculated, Figure 10. Below depicts the total labor hours divided by the number of Aircraft assembled for FODXSYS and manual.

FODXSYS reduces the total amount of labor performed for each aircraft by approximately 45% due to reducing the inspection labor and repair labor required per aircraft, supporting the production of more aircraft.

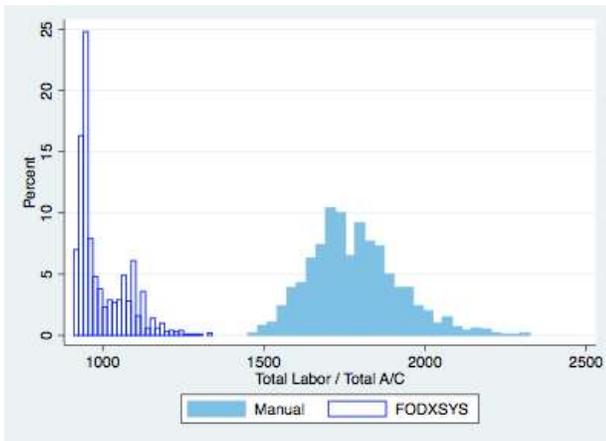


FIGURE 10
DISTRIBUTION – TOTAL LABOR/ TOTAL AIRCRAFT ASSEMBLED

VI. Business Case Results

There are 5 critical locations where the inspections will take place, using FODXSYS, therefore, \$10M as an initial investment was required since we chose to use the highest priced X-ray alternative (\$2M) to compensate for any unexpected costs encountered throughout the lifetime of FODXSYS.

As depicted in the figure below, a break even point is expected 5.5 years after implementation.

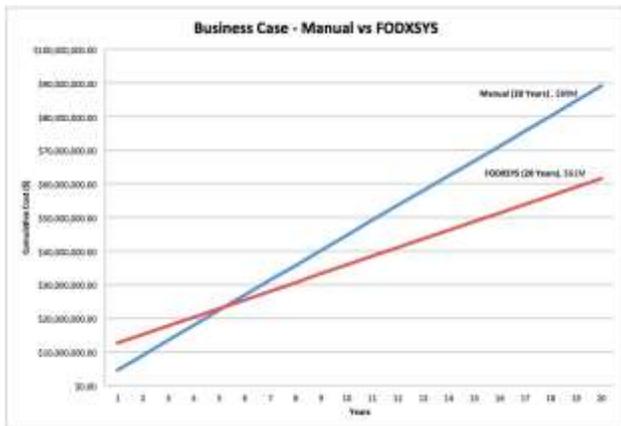


FIGURE 11
MONETARY ANALYSIS – CUMULATIVE COST VS YEARS OF PRODUCTION

Profit can be expressed as cumulative hours; approximately \$8M is the expected savings 10 years after; \$18M after 10 years, and \$27M after 20 years is expected in cumulative savings.

CONCLUSIONS AND RECOMMENDATIONS

Ultimately, the installation of the enhanced X-Ray inspection system, FODXSYS, is recommended. The system successfully addresses the majority of the issues that are associated with the manual-visual inspection method through by-passing line-of-sight visibility restrictions and proving that a probability of FOD detection of 95% is

possible. Simulation results of the production line have indicated that FODXSYS will improve aircraft production by considerably reducing total inspection hours as well as FOD-related rework hours through eliminating the majority of the severe rework cases. The study positively concludes that, by increasing the probability of detecting FOD at earlier stages of manufacturing, considerable costs may be averted from rework later in the production line.

Sensitivity analysis indicates that, if there is a possible method to increase the probability of FOD detection for manual inspection up to approximately 80%, manual inspection would be a comparable, and potentially more efficient, method than FODXSYS. Figure 12 depicts simulation results for rework hours and aircraft quality upon delivery, between different probabilities of detection for the manual method alongside FODXSYS, the graph indicates that the cost and quality of FODXSYS can only be achieved by the manual system through dramatic improvement to the probability of detecting FOD. Yet if improvement up to 80% is possible through manual inspection it is recommended. As displayed in the graph the phenomenon known as diminishing returns occurs after passing 80% probability of detection.

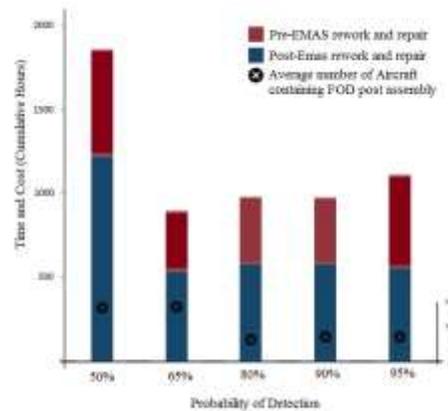


FIGURE 12
TIME COST QUALITY SENSITIVITY ANALYSIS - MANUAL VS FODXSYS

ACKNOWLEDGMENT

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