Internship Report

Operational Excellence & Technology at Lockheed Martin

Spring 2024

Moritz Genzwuerker
LOCKHEED MARTIN - TERMA
86 S Cobb Dr SE

LOCKHEED MARTIN TERMA DTU

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Introduction

During the spring of 2024, I had the distinct pleasure of participating in the Lockheed Martin Internship programme in cooperation with Terma A/S. This report details my experience working at Lockheed, the projects I was involved in and my time in the US.

Due to the confidential nature of the work done at Lockheed Martin, the main sections of this report contain no proprietary information. To aid the continuation of the projects I was involved in, all relevant documentation for my work can be found in the appendices, which are not intended to be viewed by personnel outside of LM.

This rotation of interns consisted of three graduate-level engineering students, including myself, from the Technical University of Denmark and Aalborg University. We have collaborated extensively on all of our projects. The majority of the work presented in this report is therefore the result of the collective efforts of myself, Johannes Bach Larsen [AAU] and William Lysholm Kappelgaard [DTU].

Background

The Lockheed Martin Terma Internship Program offers the unique opportunity for engineering students enrolled at a Danish university, such as myself, to spend 5-6 months working in the United States.

The internship is based at Lockheed Martin Aeronautics' impressive production facilities at either its Fort Worth [FTW], Texas or Marietta, Georgia location. We, the interns, get the opportunity to work on the fighter jet of tomorrow, the Lockheed Martin F-35 Lightning II. The aircraft is called a multirole fighter and will form the backbone of many of the world's future air forces. It is to be produced in numbers exceeding 3500 units.

In Georgia, we are a group of three people who work, travel and live together. At Lockheed, we participate in projects, complete courses, interact with mechanics and fellow engineers, and work directly with the aircraft.

Projects

This section of the report provides brief overviews of the projects I was involved in during my five month stay at LM. There is a culture around interns picking their own projects and/or picking up projects from previous interns. The review of past interns' work was completed during the first two weeks and provided valuable insights into the nature of the work expected from us. The previous internship reports provided useful information, particularly those of the previous Dutch interns, whose work acted as the groundwork for our projects. Hopefully this report will act as a similar guide for future interns.

Automated Sanding of Aircraft Parts

My main task and the project that I spent by far the most time on was the development of an automated sanding platform based on a UR10e robot arm. The project aims to partially automate the sanding of primer and OVERCOAT on the rudder of all three F35 models. Provided the platform proves itself, this setup may be implemented to sand all coated parts of the aircraft. The project has gained a lot of attention from all stakeholders, especially ESH engineers and LM management as the current process, which is hand sanding of all parts, is slow and puts a lot of strain on the operators' arms and shoulders. This system will ease the job of the people painting the F35 and massively reduce occurrences of repetitive strain and vibration injury. There are a lot of requirements to the project but they can essentially be captured by the following:

- The system has to work collaboratively with mechanics and painters, in the current production environment in Building 3 at LM Marietta, without the possibility of harming or interfering with human personnel.
- The robotic sanding system should not run slower than current human operators.
- The sander must not remove more than the specified amount of primer/paint.
- Aircraft parts sanded by the automated solution must not require any re-work.

Background and Initial State

Figure 1 shows the setup of the robotic sanding system. A UR10e collaborative robotic arm is mounted on a prototype cart intended to dock to different fixtures around the production floor. The arm is equipped with the Ferrobotics Active Contact Flange kit [ACF kit] and a pneumatic orbital sander. The ACF kit is specially developed for cobots that automate previously manual surface treatments. The ACF allows the user to regulate the contact force between the sanding disk and the workpiece. It can account for deviations and curvature in the sanded part (very relevant for the sometimes extreme contours of the F35's skin) because the end effector allows for 35mm of travel perpendicular to the sanded surface, though this has some limitations (more on this in Appendix A1). The entire system is mobile, however requiring hook ups for power, compressed air and vacuum to operate. The sanding end effector connects directly to the shop vacuum to immediately clear any dust resulting from sanding.

The entire system is easily programmable using RoboDK and the Ferrobotics web interface that comes with the ACF kit. The whole system is controlled using the UR Teach pendant that comes with the robot.

Figure 1: Robotic Sanding System

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When I arrived in Marietta, the robot had been partially set up and connected to the ACF kit, but it had never been used. The project was still in its infancy, with only the critical hardware having been purchased and moved to the OpsTech Robotics Lab in Marietta.

Development of Automated Sanding so far

This part of the report gives a very high-level overview of the work done on the project during the spring of 2024. To avoid interfering with LMPI regulations, this section does not include any technical details, which can be found in Appendix A1.

During the first weeks of the internship, I focused on learning the basics of RoboDK, the capabilities of the UR10e and how to interface with the Ferrobotics toolkit. As a first demonstration of the system's capabilities and my ability to program said system, I got the robot end effector to follow a highly contoured surface (with a slight offset), proving that sanding of complex geometries is feasible. This capability, of course, comes with the caveat that any valley or recess in the sanded part cannot be narrower than the diameter of the sanding disk. This was technically the case for the part used in the demonstration, but it still looked promising enough, enabling us to continue the project. Early testing quickly showed that the physical setup of the robot, especially the pneumatic tubing, needed to be installed more robustly for a production environment. We, therefore, spent a few days upgrading the robot cart and improving the wiring. Since then, the robot has also been encased in a protective sleeve to prevent paint residue or dust from damaging it.

After successfully completing the non-contact demonstrations, we transitioned to the project's next phase: sanding on actual material. This marked a significant step forward, as we began sanding on 1ft by 1ft aluminium plates (coupons) directly mounted to the robot cart. The sanding was conducted at different inclinations, once at no angle and once at an angle of around 20 degrees, further showcasing the system's versatility.

Following the preliminary demonstration, we transferred the robot from the laboratory, where we conducted the aforementioned tests, to the actual production environment in B3 of Airforce Plant 6 in Marietta. This move was necessary as we were moving on to sanding material that was coated with F35 paint (primer and Overcoat), which we could not do in the limited laboratory space where we initially conducted our tests. The first runs showed promising results; the feedback from an area supervisor was that our sanded coupons were suitable for further painting.

We discovered through conversation with a process expert that human operators will generally sand parts while holding the sander at a slight angle. This eliminates "chattering", which occurs when the sander isn't perfectly aligned with the workpiece or the contact force is insufficient. We tried to implement this for the robot but quickly learned that this would result in over-sanding, which is undesirable. In general, we concluded that mimicking human behaviours with the robot arm, such as moving the sander across the workpiece in circles, is not the correct approach. The robot can sand more efficiently than a human operator by doing linear passes while maintaining full, flat contact (meaning less wear on the sanding disk) with a slight overlap. At the time of writing, we are still working on tuning the robot's parameters. These include:

Sanding Force: The force the ACF kit applies perpendicular to the sanded surface. This force can be controlled in real-time by RoboDK, meaning it is technically possible to adjust the sanding force when sanding across a changing geometry or when transitioning from primer to topcoat.

Sanding Speed: The movement speed of the UR10e robot arm. RoboDK can also control this parameter in real-time. The only limitation of this variable is safety. The robot will work alongside production personnel, and making it move too quickly will put human operators at risk. Despite this, we naturally want to sand as fast as possible, without sacrificing quality, to decrease the time spent on each aircraft.

Sander Air Pressure: The air pressure supplied to the orbital sander. It needs to be high enough to sustain a constant RPM during sanding. This parameter has to be optimized to work on all geometries with primer and Overcoat, as changing it has to be done manually by turning a wheel on an air regulator mounted to the outside of the cart.

Overlap: There is a small amount of flex in the sanding disk. This means the sander removes more material from the centre of the contact area than the outside. To correct this, parallel sanding passes should have some degree of overlap. This needs to be tuned to where the surface is sanded evenly (without any striping) while not removing too much material or wasting time by doing unnecessary passes.

Sanding Angle: Theoretically, it is possible to angle the sanding disk. Realistically, that means changing the angle of the sanding pad between 0 and 5 degrees from parallel to the workpiece.

Tuning these parameters is challenging as we do not have an accurate way of quantifying the quality of the sanded workpiece. Inspection of a sanded part before painting is done by eye or using pass/fail measurement tools. We, therefore, elected to postpone conducting a full design of experiments and instead tried to find some parameters that allow the robot to sand reliably.

The overall development plan for the project can be seen in Table 1.

Table 1: Objective Based Development Plan

Objective	**Perform sanding and painting operations on multiple parts robotically without human intervention**		
Objective based development	Stage 1: Sanding Flat Primed Parts	Stage 2: Sanding Primer and Overcoat	Stage 3: Sanding under Reduced Supervision
Cycle time	The process time can be at most 10% above manual sanding	The process time can be at most 10% above manual sanding	The process time can be at most 10% above manual sanding
Setup Time	Experienced mechanic must be able to set up in 7.5 minutes	Experienced mechanic must be able to set up in 7.5 minutes	Experienced mechanic must be able to set up in 7.5 minutes
Contact Force Feedback Control	No force control	Edge areas may require less force, thus active changes in force, thus strict localisation or force changes are required	Edge areas may require less force, thus active changes in force, thus strict localisation or force changes are required
Localisation accuracy	Only low accuracy required, only large flat surfaces sanded,	Localisation to within 5 mm, as blend regions are treated differently	Localisation to within 1 mm, as blend regions are treated differently
Required Supervision	The robot must be supervised entirely, and all accessories must be manually applied	The robot must be supervised entirely, and all accessories must be manually applied	The system must be able to change between programmed paths and must be able to position it self or the work piece to execute these.
Uniformity of sanding	The primer coat cannot be burnt through, large variability is acceptable, striping acceptable	No burn through, variability acceptable, stripes with a diameter less than 10mm acceptable	No burn through, variability acceptable, stripes with a diameter less than 5mm acceptable, must be able to sand the curved parts of Vertical/ horizontal stabiliser and the rudder.

Future Development

While I managed to prove the competence of a robotic sanding solution, the system still requires a lot of tuning. An extensive parameter study needs to be conducted to achieve maximum HPU (Hours Per Unit) savings while maintaining a consistent level of quality for the aircraft. The system would also greatly benefit from the implementation of statistical process control (SPC), which would make the robot aware of what it's doing, allowing it to trigger a protective stop so as not to damage the aircraft or possibly even adjust on the fly and continue sanding without human intervention.

At the time of writing this report, we have yet to sand on aircraft parts and have very little experience when sanding on Overcoat, which is a lot tougher to sand. Human sanding operators compare sanding Overcoat to sanding on tile, requiring a lot of force. I expect this to be a problem as this might trigger the robot's protective stop, which is necessary to allow it to run in a production environment. I have not had time to investigate this issue further, but I hope my research into the optimal primer sanding will form a good starting point for sanding Overcoat. Overall, much more testing is required for the robot to be sanding in production independently.

For enhanced operation, the robot will be equipped with a tablet and a comprehensive Human-Machine Interface (HMI). This HMI will empower the operator to program the robot on the spot, providing instructions on what to sand and guiding through a list of safety checks. This feature is a significant step towards autonomous operation and is currently being tested in Lockheed's Fort Worth side, with plans for implementation in our project.

Audits

PBS Audits

The Quality department at LM performs PBS (Process Build Surveillance) audits on mechanics in regular intervals. They do this to guarantee the quality of the product and prevent a faulty product from getting delivered to the customer. Mechanics regularly fail these audits for example due to lack of knowledge when quizzed about a specific standard, due to incorrectly performing a certain operation or due using an incorrect tool. For example a common failure appears to be mechanics “feathering” the trigger of a drill instead of using a drill that runs at the correct rpm. To get ahead of PBS failures, the OpEx department performs PBS-style audits in order to get ahead of quality failures. During our internship we had the opportunity to shadow production experts during these audits, learn what mistakes to look for and how to work on aircraft.

AS9100 Audits

AS9100 is a standardized quality management system that Lockheed Martin and most other aerospace companies have adopted. To guarantee compliance with this standard, an external company audited Lockheed during our internship. The audit involves interviewing mechanics about their work and testing their knowledge of the systems they use daily. Before the audit, we spent around a week preparing the mechanics on the production floor for the audit. This meant interviewing as many people as possible on topics in which we were not entirely fluent. The whole process was a fun challenge, made us more comfortable with the production environment, and helped us build connections with some of the mechanics. This would later be extremely helpful in my other projects.

Blueprints and 3D Models for the Training Department

During my internship at Lockheed Martin, I was given the opportunity to help fill a gap in the training department. The company trains and educates their own mechanics, providing in-depth classroom training on software like Shopfloor Management (SFM), reading blueprints, and more. Additionally, they offer a lot of hands-on training where new mechanics learn how to work with different materials, drill, countersink, install, seal, and inspect different parts. However, traditionally, this training has been done using small test pieces that do not resemble actual aircraft in terms of complexity or appearance. In reality, mechanics need to be able to work in different positions and learn how and which tool to use to get to difficult spots. Therefore, the training department needed more realistic and challenging training pieces that were similar to actual aircraft.

I helped design, build, and blueprint several new training parts that were more realistic and challenging for the trainees. This involved working closely with the trainers to understand their needs and requirements, and then modelling different fixtures in CATIA. Almost all fixtures were 3D printed, some with attachment points for sacrificial metal plates through which the mechanics could drill. A lot of the work consisted of learning how to make blue prints according to aircraft standards, which the mechanics would then use in training to complete their projects. This task proved significantly more challenging and time consuming than expected as some of my blueprints had to be made in accordance with C-130 standards. When the C-130 was designed, blueprints were still drawn by hand and therefore looked very different, offering much fewer and less detailed views to the mechanic. Imitating the drawings with modern CAD software took several weeks and by the time of writing this report I have not completed this task.

This is one of the longest running tasks I have had at Lockheed, and while I was never able to prioritize it over my other projects I learned a lot about interfacing with a constantly changing project and adapting to customer feedback.

Statistics Based Selection of Mechanics for Re-Training

As indicated in the previous section, Lockheed Martin trains their own mechanics. Since the training department is constantly trying to modernize and improve its approach to training mechanics, this leaves older mechanics with some gaps in their knowledge. There is also a trend of supervisors assigning their experienced mechanics to the tasks they excel at while getting others to cover their knowledge gaps. This becomes problematic whenever there is an immediate need for a mechanic to perform a task outside of their comfort zone. Older mechanics may not know how to perform some basic functions as they weren't required to perform them in years. For this reason the OpEx department is implementing a mechanic re-training program. Mechanics who have been working at the company for a significant period will be pulled back into a special shorter training program to update their skills on all tasks. This effort will not only increase the overall knowledge and knowledge exchange around the production floor but also hopefully increase PBS scores, leading to improved performance across the board. To make the biggest impact with this program, the "worst" mechanics on the production floor will be selected for re-training first.

During my time at Lockheed, I developed an analytics tool that monitors mechanics performance based on several metrics: Process Build Surveillance Score (PBS Score), First Pass Yield (FPY) and Quality Assurance Review entries (QAR entries). The tool takes into account the mechanics' level of seniority and the number of audits they have been subjected to. It does this via a method based on Bayesian probability, where an initial belief about a mechanics score in a certain metric is weighted against their actual score. This means that the algorithm treats a mechanic with many audits but a slightly lower PBS score more favourably than a mechanic with few audits but a higher PBS score. The user can define weights for all metrics, as all metrics do not equally reflect the mechanics skill level. This will trigger the algorithm to recalculate based on the new weights. In the example shown in the figure, QARs are prioritized over FPY and PBS meaning mechanics with otherwise high scores will be listed first, if they have an above average number of QARs. It then provides the user with suggestions for training groups in decreasing order of priority. Some mechanics are ineligible for training, sometimes due to them being leads for their area or having been relocated, which is not always reflected in the data. In these cases, a given mechanic can be exempted from the ranking. This gives the person selecting mechanics for training an additional level of control and is intended to future proof the software.

At the time of writing, there are still some kinks in the programming, they main one being that the calculator runs based on inconsistent data. The algorithm is fed by excel files downloaded from a database, but at the moment these have duplicate entries, inconsistent identification of mechanics (some have employee numbers, others have names in different formats) and conflicting data points. I am currently working on making the tool robust enough to accept all data pulled from various internal databases without any additional user intervention.

To add more nuance to the training groups suggested by the calculator, I am currently looking into how to include additional metrics such as mechanic rankings put forward by floor supervisors and the number of positive and negative feedback interactions that a given mechanic may have had. When I manage to include these features, the tool should provide a comprehensive picture of a mechanics skill level.

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Figure 2: Screenshot of the dashboard of the mechanic training calculator. Employee Names have been censored and data falsified.

Slider Safety System

During the final stages of the centre wing's assembly at Marietta, the aircraft is stood up vertically. This means that mechanics can work on the aircraft (ship) while standing on ground level and while working from a platform about 15ft above the ground. In order for mechanics to get close enough to the structure to work on it, a set of 19 total sliders encompass the centre wing and provide a platform for the mechanics to stand on.

At the moment a control panel (Figure 4) gives the mechanic full command over the position of the sliders (Figure 3). It turns out that this creates a massive safety issue as a mechanic may not extend the sliders close enough to the aircraft to prevent a falling hazard which Lockheed defines as any gap exceeding 12”. In many cases the sliders will not be fully extended to allow mechanics to work from above and below simultaneously. This is dangerous for mechanics working on the pl[...] with any form of safety gear, fall arrestors or similar. Me[...] in danger of being hit by tools/clamps, should a mechanic wo[...]tally drop something.

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Figure 3: Birds eye view of Sliders

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Figure 4: Control Panel

At the time of writing this report, I am investigating ways of mitigating or even eliminating the hazard described above. I am currently looking into a mechanical solution that could be retrofitted to the sliders which would prevent a mechanic from being able to retract or extend the sliders to any point that might incur a falling hazard. As an alternative and cheaper solution which is less invasive and does not obstruct the mechanic’s workflow I am also working on proposals for active and passive warning systems. At the time of writing a final design has not yet been selected.

This project was one of the most interesting things I have worked on at Lockheed due to the high number of constraints. The sliders are technically owned by the US government and modifying them requires a lot of paperwork and a very good reason. There is also a lot of pushback from the mechanics on the production floor towards anything safety related as the implementation of a mechanical solution would force them to change their workflow and likely spend additional time following proper safety procedure. While everyone is aware of the apparent danger that the current design of the sliders pose, I have at many points been forced to answer questions like: “I have never heard of anyone having fallen, why should we change this?”. The reluctance to implementing safeguards, combined with a loosely defined but strict budget taught me a lot about engineering change in highly constrained environments.

Ad-hoc tasks

Mechanic Training Baseline

While at Lockheed, the training department started rolling out a new training project for mechanic re-training. It involves drilling and countersinking holes in a highly contoured fibre composite surface. To form a baseline for how fast a mechanic would complete the training task, I got the chance to go through the mini-project. Before working on this, I had yet to learn how to drill or work with anything other than wood or aluminium. Even though completing the training piece took me much longer than it most likely would have any mechanic from the production floor, I learned a lot about mechanics' challenges.

Helping with Sealant AI and ADMIRAL

While I was not directly involved in these projects, I spent a lot of my time during the internship helping with two other cutting-edge development projects. The first concerned the robotic inspection of seal caps in the fuel bays of the F35, and the second was the rollout of an automatic shim delivery system that would decrease mechanics travel and wait time.

Chemical tags

I also helped develop and test a new labelling system for chemicals on the production floor. All chemicals used for work on the F35 (sealant, click bond, etc.) must be tagged with a date label to ensure no expired chemicals are used on an aircraft. Before the rollout of the new system, the labels would show the date when the chemical was first used. This led to many expired chemicals being found around the production floor, as it was not always immediately apparent whether a compound was expired. The new system will print the date of last use based on what chemical has been opened, making it much easier for mechanics to control their inventory.

Trip to Fort Worth

As part of our internship, we visited Lockheed's massive facility in Fort Worth, Texas, where the final assembly of the F35 takes place. Apart from allowing us to catch up with the other interns and learn about their experiences, we gained much insight into the complexity of the product. This was not always apparent since, at the Marietta plant, we only get to see and work on the centre wing. Realizing the full scale of the assembly felt like an important step and made me realize the importance of us at the Marietta plant delivering a high-quality product. We got several tours of different parts of the one mile and 25 foot long facility. Walking along the manufacturing line and seeing how the centre wing becomes part of the whole aircraft was fascinating.

One of the noteworthy highlights of our stay was flying and landing an F35 in a cockpit simulator under the instruction of two former pilots.

Electronics Enclosure

During my stay I helped the FTW team of interns develop a casing for an AI inspection system.
Our stay in Texas was unfortunately too short for me to see it to completion.

Figure 5: The entire S24 Team of Danish Interns

Source: https://www.smugmug.com/gallery/n-QMPBCg/i-NSTQ2MW

Outside of Work

During my 6-month internship at Lockheed Martin, I had the opportunity to experience American culture first-hand. I was amazed by the diversity, hospitality, and warmth of the people. I also got to travel around a lot during my stay. I visited some of the most iconic landmarks and cities in the US, and each place had something unique to offer. Below, I provided a short list of some of my highlights in the U.S.

NASCAR Talladega, AL

Baseball Atlanta, GA

Rodeo Fort Worth, TX

Blue Angels Airshow Fort Worth, TX

Mechanical Bull Riding Atlanta, GA

Steaks & Sweet Tea Literally everywhere

Skydiving Vinemont, AL

Exploring a Goldmine Dahlonega, GA

Live music at the Grand Ole Opry Nashville, TN

Kayaking through a swamp with alligators Charleston, SC

Roadtrip to Denver (because we missed a flight) Denver, CO

New York New York

Figure 6 is meant to show all the places we have been and still want to go though we've seen much more on the way.

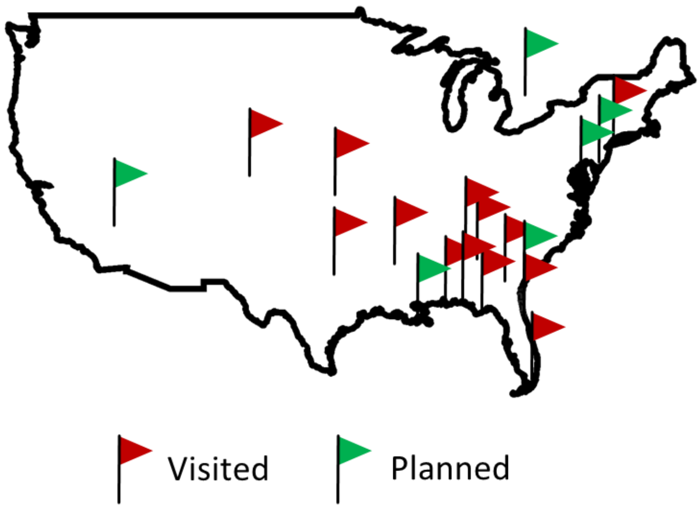

Figure 6: USA Adventures

New York	**Denver**	**Dahlonega**
Miami	**Savannah**	**Mobile**
Fort Worth / Dallas	**Charleston**	**Las Vegas**
Nashville	**Panama City**	**Chattanooga**
Saint Augustine	**New Orleans**	**Jacksonville**
Atlanta	**Columbus**	

Takeaways

One of the biggest things I've learned at Lockheed Martin is how important quality is. I had strong connections to the Danish manufacturing industry outside of aerospace before coming here, where I have learned that mistakes in the product are unacceptable. My mentors in past internships and industry projects have always impressed on me how important stable and repeatable manufacturing processes are. However, nothing that I have worked on until now had the potential of costing a human life if it wasn't good enough. One of my colleagues in the OpEx department explained the phrase "when the cheeseholes start lining up" to me. The phrase refers to a situation where multiple system failures align, potentially leading to a disaster. I learned that in aerospace, there is absolutely no room for error, and the stakes are high. This means that we, as engineers, have to approach technical challenges with additional care.

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