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Design and Development of a Mobile Robotic System for Aircraft Wing Fuel Tank Inspection

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Abstract

This paper presents the design concept behind a novel remote visual inspection robotic system for fighter jet aircraft wing fuel tank inspection. This work is part of a larger research project which focuses on design, simulation, physical prototyping and experimental validation of a robotic system. Whereas this paper specifically focuses on the development concept of locomotion design choice for the robot. Therefore without an effective mobility method the robot will not be able to fulfill its purpose to access the hazardous confined spaces of the fuel tank. Aircraft wing fuel tank inspection is a challenging area of maintenance which requires a considerable amount of preparation and involvement of several tasks in order to conduct effective Visual and Non Destructive Inspection. The environment of an aircraft wing fuel tank poses several challenges due to both physical and atmospheric constraints which can be detrimental to human personal. This paper introduces an effective locomotion design which should allow the robot to enter and maneuver within confined spaces. The robot is relatively small, approximately 70mm in height and width yet, flexible enough to move within the restricted spaces of the wing. The mobile robot platform is a combination of small track systems that articulate like a snake. An additional mobile platform deploys an inspection sensor to reach the spaces that are unreachable by the robot body. Like other proposed robotic systems this particular proposal differs as it allows the robot to enter from the root of the wing and reach the narrower spaces towards with the wing tip. This paper highlights the stakeholder requirements to illustrate the foundation of the robotic system design. An overview of current complications of wing fuel tank inspection is presented and the analysis of current proposed robotic systems for wing fuel tank inspection. An engineering design methodology approach is followed for this project. Several locomotion methods are evaluated and an innovative locomotion method is illustrated with the use of CAD models. The desired outcome of this research is to eliminate the entry or close contact with the fuel tank by human personal.

Introduction

The Eurofighter Typhoon fighter jet is a highly agile aircraft which is aerodynamically shaped for high speed purposes. The wing design of the jet is a canard delta wing which is streamlined, narrow and compact. The jet fuel is stored within several areas across the aircraft body, with the main storage area being the wing structure, in both AFT and FWD fuel tanks. The jet fuel is stored directly within the wing assembly also known as ‘wet wing’ and is able to transfer across the wing structure through flexible fuel ducts and fuel transfer holes. Figure 1 [1] shows the internal structure of the Typhoon wing during the build and assembly process and features the fuel transfer holes found along the spar structure. It is visible that the wing structure is very narrow. The fuel transfer holes are allocated across the spar structures and are approximately 70mm in width.

The wing of a fighter jet aircraft is much narrower in comparison to that of a A320 wing and the subassemblies within the wing pose additional difficulties to access certain areas for inspection, specifically confined spaces towards the wing tip. Therefore, disassembly of the wing box is required in order for an engineer to gain access to the area of inspection. Other than the narrow spaces of the fuel tank there are other hazards such as presence of toxic vapor emitted from the jet fuel and lack of oxygen which makes the fuel tank environment a hazardous space to work in.

The motivation behind this project is to reduce or eliminate the exposure of toxic substances to engineers conducting inspection. The research focuses on evaluating current state of the art technology of robotic systems and developing new concepts of a robotic system for aircraft wing fuel tank inspection, primarily focusing on visual inspection. One of the key requirements is that the robot should have the capability to enter the confined spaces of the wing assembly to conduct inspection. The use of robots can help reduce time spent on overall inspection tasks in both preparation and disassembly and protect engineers from the dangers of the fuel tank environment.

This paper demonstrates the physical structural design concept of the robot based from the developed set of requirements. This research follows a strategic engineering design approach which is described in further detail in the methodology section.

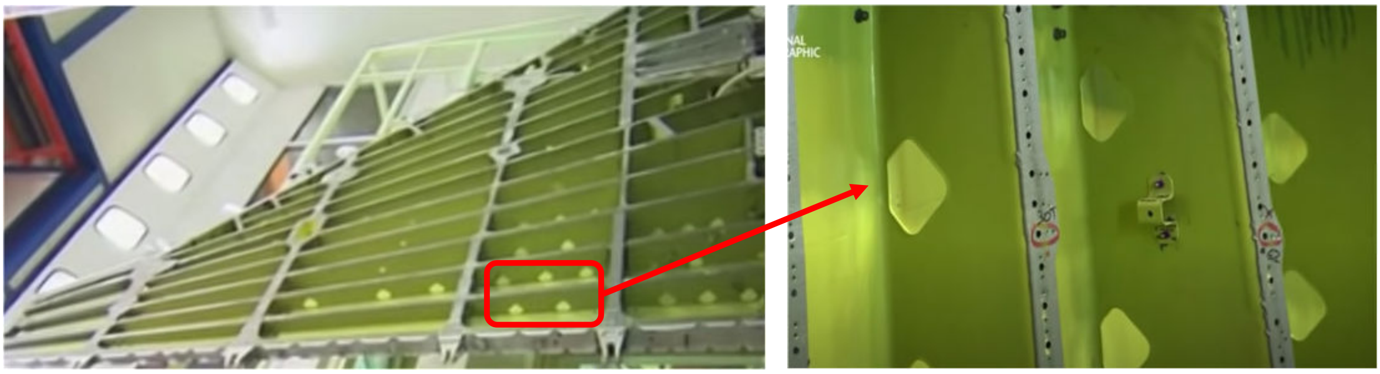

Figure 1.Eurofighter Typhoon multi wing spar structure with fuel transfer holes.

Aircraft Wing Fuel Tank Inspection

The key purpose of inspection is to identify any discrepancies that may hinder the functionality of a system. Different types of defects can be found within a fuel tank such as surface damages, fuel leaks and microbiologically initiated corrosion. Visual inspection or Non-Destructive Tests (NDT) are conducted to detect these defects and initiate appropriate repair tasks.

Current maintenance practice of inspecting the fuel tank involves a qualified engineer entering the fuel tank through a small opening in the wing, in which they are required to manoeuvre within the fuel cell compartments, equipped with necessary respiratory equipment and Personal Protective Equipment (PPE) for protection. This process works better in larger wing structures.

Inspection of smaller aircrafts are conducted with the use of Remote Visual Inspection (RVI) equipment such as a borescope which is fed through an access hole which are found at several locations across the wing. Borescopes are popular tools used for visual inspection in difficult areas due to their flexibility and miniature size, with diameters varying between 5mm – 8mm. However, a borescope may not be sufficient enough to inspect narrow spaces and would still require the additional task to remove certain panels to gain further access, since physical entry is not possible and can still expose the engineers to the hazardous environment.

Confined space is defined as an area large enough for an individual to enter and perform work but has limited restricted means of entry and exit and is not designed for continuous occupancy [2]. Fuel cells, storage tanks and pipelines are categorized as confined space areas. The Piper PA-28 aircraft have faced problems relating to the difficulties of inspection in confined space, where wing spar corrosion is becoming a serious issue in hard-to-reach spaces and inspection is challenging. Without appropriate maintenance to tackle this, it can lead to fatal failure [3]. The FAA has introduced regular inspections and new access panel installation on the wing to access these confined areas or preferably conduct wing removal.

Lufthansa Technik have also raised their concerns with fuel tank inspection implications where towards the outer tip of the wing the structure becomes narrower and lower and the frames with narrow openings make it difficult to access the spot where the defect is located [4]. Therefore it is important to tackle this common problem. By introducing a robotic system there can be several benefits and would be the most suitable solution for confined space inspection.

Challenges of Aircraft Fuel Tank Inspection

There is a great percentage of work that involves maintaining an aircraft fuel tank including both inspections and modifications. Performing these tasks requires personnel who are physically fit to work with in such a complex environment where several hazards are present. The protentional hazards within a fuel tank environment include:

- Fire and explosion risk
- Toxic and irritating chemicals
- Oxygen deficiency
- Physical restrictions of confined spaces

Physical characteristics' of the tank can create many implications. The entry point of a fuel tank tends to feature an oblong shaped hole which is less than two ft (0.6m) long and one ft (0.3m) wide. The physical dimensions of the wing structure change between the inboard and outboard section of the wing since the wing structure becomes more narrower towards the outboard section of the wing. The center section of the tank is large enough for an engineer to fit in however, the most outboard section of the wing tends to only have enough space for a personal's hands and arms. Figure 2 shows an example of an engineer crammed inside a wing fuel tank conducting inspection. It is also noticeable that the conditions are dark within the tank with very little natural light entering through. Therefore, the engineers are required to carry a flashlight to thoroughly observe the area of inspection. Restricted spaces also pose difficulty to see clearly behind assembly structures. Figure 2 also shows a human personal wearing protective equipment before entering the tank and it is also noticeable that the they are just about able to fit within the access hole of the tank.

The interior dimensions of smaller aircraft differ greatly than that of larger aircraft, like the that of the Piper PA-28 and military fighter jets fuel tanks are relatively small and the chemical substances inside these small enclosed space can create significant levels of flammable toxic vapor.

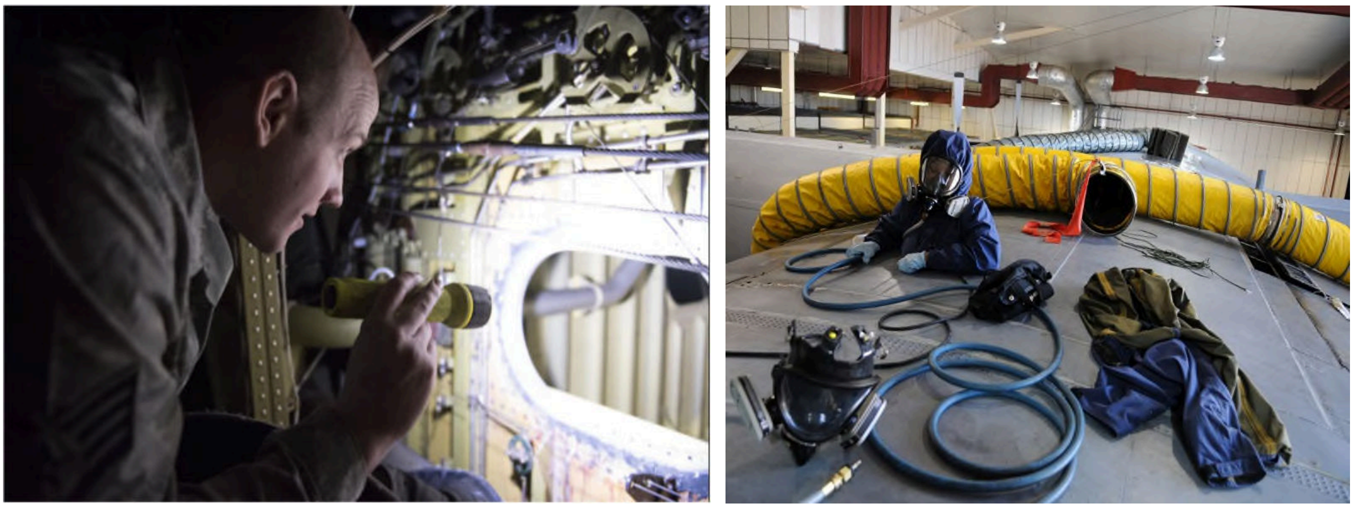

Figure 2. Engineer using flashlight to inspect fuel tank and personal in fuel tank wearing protective equipment during inspection

During fuel tank inspection the use of electrical equipment is limited and with the necessary electronic standard certifiction certain equipment such as flash lights can be used during inspection as long as they follow the specified regulations. The equipment has to be intrinsically safe so that it is not prone to explosion. For this research the US Military technical manual [6] for aircraft fuel tank inspection has been used as a basis of this study by understanding the implications of preparation of the fuel tank before maintenance.

Current Proposals of Robotic System for Aircraft Wing Fuel Tank Inspection

An overview of the current proposed robotic systems for wing fuel tank inspection are discussed highlighting critical design parameters of each system. A number of robotic systems have been proposed over the past several years for the challenging environment of the fuel tank and is still a relatively new area of research. A continuum arm robot design has been proposed to enter the fuel tank to conduct inspection with the incorporation of an autonomous path planning system. The key design aspect of this robot is that the electrical system of the robot should remain on the outside of the fuel tank in order to prevent the risk of explosion [7]. This concept is beneficial for the hazardous environment as it eliminates the risk of explosion yet it has the flexibility to bend into the confined spaces of the wing due to its snake arm robot design. However, one of the drawbacks of this design would be the amount of surface area of the internal tank it the robot would be able to cover for inspection, especially the confined spaces of the fuel tank. It also does not have the capacity to hold several sensors since it is only able to have an end effector only attached at the end of the arm. The Hexapod [8] is another example of a robotic system developed which is a mobile robot that is able to crawl into the fuel tank from the root section of the wing.

This is a good example of the application of creating a mobile robot that would be able to fully enter the fuel tank. The choice of locomotion for this robot is walking, yet this method does pose several limitations. Walking locomotion method may not be the most convenient design for maneuvering through the structure of the fuel tank. The robot may be unsteady in the fuel tank due to the surface area that each leg is able to cover. The leg of the hexapod is also prone to get wedged and obstructed within the stringers of the fuel tank which can cause the robot to topple over if it cannot release itself. This design is not efficient for the purpose of inspection in complex spaces. Since the robot has numerous limbs it also creates the possibility to come into contact with the structure of the fuel tank which can have a damaging effect. The safest option would be to reduce the amount of movement produced by the robot in the fuel tank so that it cannot damage its surrounding structures, which is again based on the robot chassis design. The hexapod robot has the possibility to move within the larger sections of the wing fuel tank but cannot access the confined spaces due its large dimensions. A second example of a mobile robotic system developed is based on applying caterpillar track locomotion as a method of mobility. Figure 3 [9] shows the tank robotic system placed in an experimental rig of a B737 wing fuel tank. The robot has been specifically designed to inspect a B737 fuel tank. Similar to the hexapod the concept of the mobile robot is efficient for the large areas of the wing box for inspection however, similar to the previous concepts highlighted the dimensions of the robot still creates many limitations for accessing the confined spaces of the fuel tank and to cover a larger area of the wing box. The advantages of the track system in comparison to the other stated choices of locomotion is that it allows the robot to be able to move across the fuel tank effectively since the tracks of the robot can cover more surface area and has greater stability. Caterpillar tracks also allow to overcome uneven terrain and move through puddles of fuel residue without slippage.

Figure 3 [10] also shows the most recent robotic concept proposed for fuel tank inspection which is called the Eloscope. The main structural body of the Eloscope is designed around the concept of an endoscope. The Eloscope is designed to be as miniature as possible in order to access the confined spaces of the wing preferably for an A320 or B747 wing tank. The concept similarly focuses on reducing the amount of time spent on inspection. It also has the capability to gather images of inside the fuel tank structure for the application of a digital twin concept. The Eloscope focuses on reducing the amount of payload of its design and to eliminate the use of electrical components in order to ensure that it is explosion proof. A novel locomotion concept is designed allowing the robot to enter the fuel tank while the tank is full of fuel. The robot uses the fuel to power its thrusters in order to create a swimming motion. This innovative development emphasizes on reducing preparation time that is spent before entry of a personal and to eliminate defueling and ventilating of the aircraft fuel tank, which in return saves time spent on the overall procedure of fuel tank inspection.

The overall concept of this robotic system is very precise and covers many challenges faced throughout fuel tank inspection. Although this is a great concept there are several areas that need to be reconsidered. First of all, capturing clear images of any present noticeable defects requires adequate lighting to ensure that the images are clear however with the presence of jet fuel the images captured can contain distortion due to the liquid substance and may not be clear enough to capture defects. This also requires adequate lightening that would be able to generate enough visible light to capture clear images through the jet fuel. As mentioned in the critical review section of the paper the length of the Eloscope still requires further development in order to access larger span of the wing tank [10].


(a) Vertical movements

(b) Lateral movements

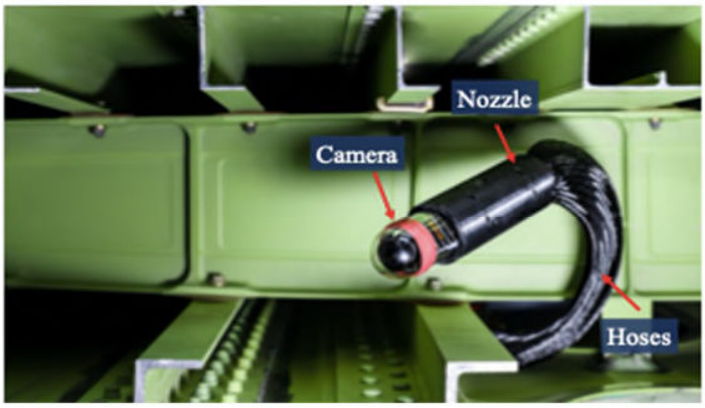

Figure 3. Caterpillar tank track robot in test rig of B737 and Eloscope concept in test rig

The Eloscope concept shows that the development of a robotic system without a necessary electrical supply onboard can be achievable and does pose many benefits. However this does not mean that electrical equipment has to be completely disregarded. Engineers who conduct inspection of aircraft wing fuel tank can still carry intrinsically safe electrical equipment during inspection such as a flash light. Therefore it can be possible to develop a robotic system that is able to have electrical equipment on board yet it should meet the requirements of having efficient amount of power supply without being prone to explosion. As stated Entry safe conditions of non-intrinsic safe equipment is 300 PPM. Oxygen concentration between 19.5-23.5 percent. Levels above 23.5 increases the risk of a fire.

The proposed design concepts of each fuel tank inspection robot has both advantages and limitations. There is still however a gap in knowledge of understanding the key characteristics of the fuel tank environment and implementation of a successful robotic system to conduct inspection in the confined spaces of the fuel tank and to also be able to cover the full wing area. The mobile tank robot and hexapod have demonstrated the idea of allowing a mobile robot to enter the tank with on board electronics whereas the Eloscope has been able to overcome the aspect of entering confined spaces to some extent but does not incorporate the use of many electronic components such as sensors which may be required throughout inspection.

Therefore there is yet a research area to overcome in the development of a robotic system that is able to be entirely mobile and access all areas of the fuel tank including confined spaces with the ability to carry several electrical components yet be intrinsically safe. Industries such as oil and gas, nuclear decommissioning have been developing robotic systems over several years and are much more advanced in the level of maturity of miniature robotic designs that are able to manoeuvre within complex pipelines, with electrical components onboard and be able to withstand hazardous exposure of chemical substances with the use of safety enclosures that store the electrical energy with the application of appropriate material to encase the robot to protect itself and the environment. The idea of soft plant like growing robotics especially within nuclear decommissioning are evolving as they have the capability to access confined spaces and do not damage surrounding structures but they are still restricted in carrying numerous onboard sensors due to payload complications.

It is predominately noticeable that majority of the robot locomotion design for pipeline inspection robots incorporate different methods of mobility primarily flexible robotic snakes which contain a number of modular sections. Which allows them to move in the confined spaces and bend around obstacles. OC Robotics are also currently working with FAA US Military to create a robot for fighter jet fuel tank inspection [11]. OC robotics have continuously worked on the development of continuum robots focusing on flexibility in mobility and with the purpose of the robots to be able to conduct inspection and repair.

In summary the endoscope robot is extremely favorable when it comes to payload requirements and to ensure that the robot is small enough to enter a variation of spaces. However, the robotic system is limited to the number of additional sensors or equipment on board due to constricted payload and can prevent gathering additional beneficial data. Therefore, there is room for the development of a robotic system that would be able to carry more electrical components that are intrinsically safe. If this is possible the robotic system can serve several purposes such as the addition of nondestructive sensors for further detailed testing.

The MINBOT is a tracked robot that was developed focusing on the unstable environment of coal mines and developed the robotic system with the use of explosion proof enclosure and explosion proof design of its electrical system [12]. Explosive atmosphere standards are used in many of these robots and materials to prevent the build-up of static energy.

The inspiration behind this project is based on research predominantly found across industries such as oil and gas and how these concepts can be adapted to the aerospace manufacturing sector. From the evaluation of all these designs, it was important to brainstorm and use the knowledge from these robotic system designs and start to develop conceptual designs for proposed aircraft fuel tank inspection robot, specifically focusing on confined spaces and the physical size of the robot. Overall adapting the compactness of a small robot is always an ongoing challenge. The primary focus is to develop a novel mobility design.

Robot Mobility Design Development

Methodology Approach

This section of the paper provides an overview of the initial design stages of the robotic system and the final concept of design for the chosen locomotion method. For this project a strategic engineering design approach is applied as described in the following stages:

- Define the purpose of use of the robotic system. This involves defining the requirements and constraints and the problem scope.
- Highlight the ‘As-Is’ current method of inspection and ‘To-Be’ case if robotic system is to be implemented successfully.
- Defining the geometry of the robotic system such as system and component dimensions.

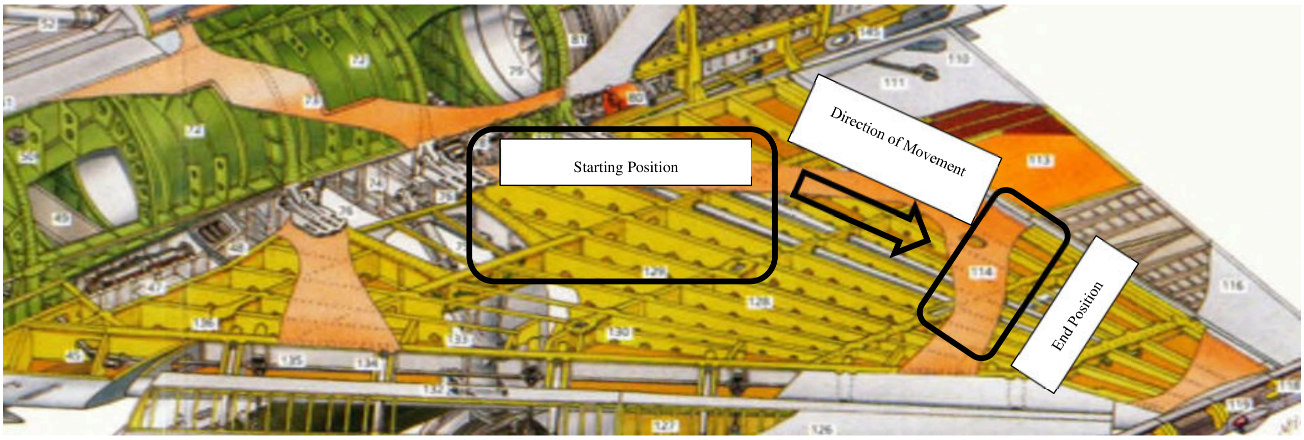

Figure 4.Cross section of Eurofighter Typhoon wing structure illustrating the proposed direction of movement of the robotic system

- Brainstorm ideas with the use of hand drawn sketches and Computer Aided Design (CAD) software for virtual simulations and testing.
- Manufacturing of physical components with the application of 3D printing and off the shelf products.
- Validation of robotic system through several experimental tests.

During the design phase and concept development there will be iterative steps which are part of the methodology to ensure that an effective concept is developed. In order to develop the project scope and configure a set of requirements for the robotic system. It is important to outline the distance that robotic system should travel from point A to B. Figure 4 [13] illustrates the route the robotic system should travel. The robot is placed down into the fuel tank on the port side wing through an entry hole. The robot system should then move to the midpoint between the AFT and FWD fuel tank. At this point the robot shall move towards the wing tip and use its onboard manipulator to extend into the confined spaces of the fuel tank. Initial requirements were developed of key parameters that need to be successfully achieved by the robotic system. An overview of the requirements are as followed. These can be found in more descriptive detail in the following paper [14].

Robotic System Requirements

This section illustrates the explicit system requirements with key parameters that need to be taken in to consideration before developing the conceptual design of the robot. The robot should meet these requirements during the experimental validation tests [15]. For detailed development of the requirements ISO Standard criteria have been integrated. Basic 2D diagrams of an initial concept of the robot are developed to illustrate in cohesive the performance criteria established from the ISO BSI requirements. The requirements are as listed:

- Robot should fit within the dimensions of the fuel tank. The fuel transfer hole dimension is approximately 70mm in width. Figure 5 illustrates the dimensions including the largest distance between each spar panel is 70mm-80mm. The height and width of robotic chassis should therefore be approximately between 40mm - 50mm in height and width.
- Robot should move within the confined spaces of the fuel tank.

  Figure 6 [16] illustrates that flexibility in locomotion method is important. For example, movement from one fuel transfer hole to an parallel fuel transfer hole requires a steering angle of approximately 30°- 45° for chassis should be feasible. Adjacent fuel transfer holes found in same spar a rotation of 90°-180° should be achievable by the chassis.

- Robot should conduct visual inspection. Noticeable visual defects of corrosion such as rust or slimy growth. Adequate lighting and camera field view of 80°(30mm) -107°(28mm).
- Robot should navigate around obstacles. 2 cable conduits approximately 2m - 3.5m in length, with a diameter of 30mm - 50mm. Figure 7 [17] diagram shows that the fuel transfer holes are found at an elevation of 11mm above the floor of the wing skin which the robot should be able move over.
- Robot should withstand the hazardous environment. Entry safe conditions of non-intrinsic safe equipment is 300 PPM. Oxygen concentration between 19.5-23.5 percent. Levels above 23.5 percent increases the risk of a fire.
- A retrieval method in case of failure. Tether should be approximately 3m - 4m in length and tether diameter between 5mm - 8mm.

Once the requirements phase was completed it was important to gain an detailed understanding of the conditions of the fuel tank environment including both physical and atmospheric characteristics. The internal dimensions of the fuel tank were defined as this would give an estimate of how small the robotic system should be. Components within the fuel tank such as fuel conduits, electrical wiring and fuel couples are all considered.

Physical characteristics of fighter wing fuel tank

Dimensional characteristics of the fuel tank are defined and provides a basis of the robot system dimensions and movement capabilities:

- The multi spar structure consists of 16 spars panels including the front and rear spar. The distance between each spar is approximately 70mm-80mm at the root of the wing and narrows down to 30mm-40mm towards the wing tip. The change in distance between the spars is due to the delta wing shape.
- Fuel transfer holes are found throughout the spar structures and are approximately 70mm in diameter.
- The transfer holes are found 11mm above the floor of the wing skin.
- The distance between each hole is roughly 130mm- 140mm apart in a linear formation.
- The rib structure formation across wing consists of 4 rib panels 7m-8m length at root of wing and 1m-1.5m at outboard.
- Two cable conduits running in line with the spar structure starting from the root of wing towards wing tip approximately 2m-3.5m in length, with a diameter of 30mm-50mm. There are also inboard and outboard elevon hydraulic actuators.
- Presence of jet fuel residue throughout wing fuel tank.

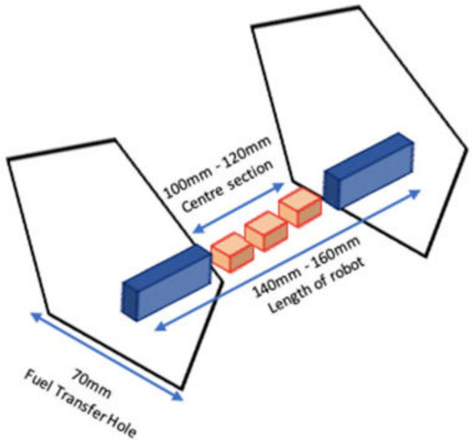

Figure 5.Example of robot overcoming sill length and width

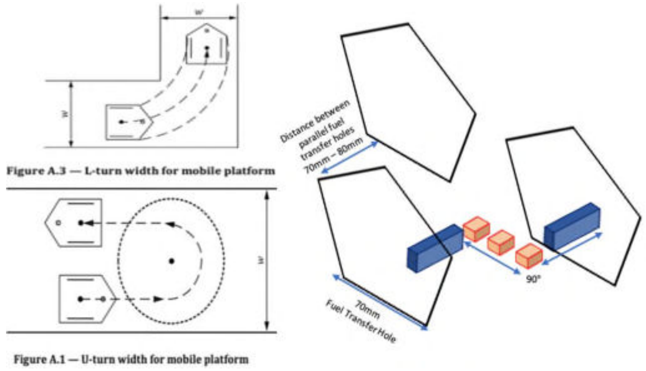

Figure A.3 — L-turn width for mobile platform

Figure A.1 — U-turn width for mobile platform

Figure 6. ISO Standard specification and example of robot turning angle

In the following section the design concept behind the proposed robot locomotion is defined.

Different approaches of locomotion were analysed as illustrated in Table 1 which solely focuses on the aircraft wing fuel tank inspection robot systems. The concepts can be grouped into two areas which are; mobile and non-intrinsically safe to enter fuel tank and secondly flexible non mobile robots which are intrinsically safe to enter the fuel tank. Both of these groups have their limitations hence why the concept proposed in this research paper will be able to overcome these limitations with further work which is currently ongoing.

Conceptual Design of Robot System

The aim is to fabricate an effective robotic system that is able to maneuver effectively within the both the large and confined spaces of the fuel tank. Current research has proposed that robotic systems should reduce or eliminate the use of electrical components onboard the robot as it enters the fuel tank which is comprehensible, however there may be limitations following this criteria. The reasoning behind the proposed design for this paper is to utilize the use of the available electrical current that is allowed for electrical equipment to be used in the fuel tank and contain it in the robot system design allowing the use of a larger variety of sensors, manipulators and tools to be used for different tasks.

The focus is primarily on mobility through a fuel tank, with the addition of a suitable method for visual inspection for hard-to-reach spaces. Awkward inspection positions can be reached by combining a linear actuated telescopic mechanism onboard a mobile robot platform which has the capability to reach confined spaces. This combination has the potential to meet the requirements of fighter wing tank inspection. This concept adapts the current manual RVI methods and merges this onto a mobile platform.

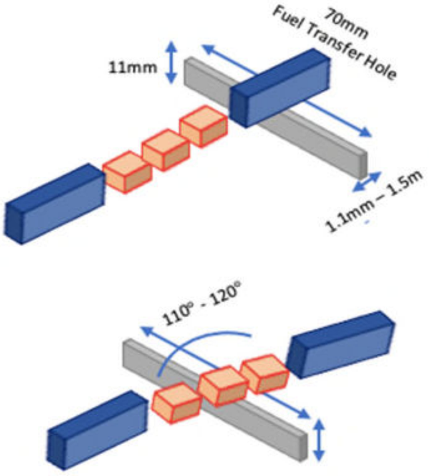

Figure 7. Example of robot bending over fuel transfer hole elevation

Locomotion Design

The choice of locomotion method relates to many of the constraints found in the wing fuel tank. Therefore, it is not feasible to select one choice of locomotion method such as a wheeled, tracked or walking robot to access all areas. The robotic system proposed combines three methods together. The robot is rigid as it compromises of caterpillar tracks and wheels yet there is added flexibility for bending and steering maneuverability. The choice of the rigid robot allows a wider implementation of several sensors and increased payload in comparison to that of a soft robot. Table 1 shows key criteria of the robot proposals for fuel tank inspection.

Table 1.Aircraft fuel tank inspection robot criteria

Robot	Inspection method	Locomotion	Navigation method	Power Source
Mechanism Design of Inspection Robot (2012)	Visual Inspection	Track Mechanism	Teleoperated	Battery Pack
Path-tracking Algorithm Continuum Arm Robot (2014)	Visual Inspection	Continuum Robot	Path finding	Tether
Introduction of mobile robot Hexapod (2019)	Visual Inspection	Walking robot multiple limbs	Teleoperated	Battery
Eloscope (2021)	Visual Inspection	Flexible endoscope concept	Teleoperated	Tether

Comparisons have been made between the different types of mobility methods as shown in table 1 and each robot has used a different method. The use of caterpillar tracks is the most suitable for the fuel tank since there is less friction produced by the rubber tracks and less slippage as presence of fuel residue puddles has to be taken into consideration. The continuum arm robot has great flexibility when bending into inaccessible places. By analyzing these two design concepts an ideation of combining these two methods of mobility was constructed. This is explained in further detail.

Mobile Robot Platform Design

Caterpillar track and wheel are used for this robot as the track system allows less slippage from the jet fuel residue and is intrinsically safe especially when it comes to friction between the track and floor of the wing skin. The tracks are designed to be single linear formation tracks as illustrated in figure 8. The flexibility in the chassis is incorporated through a center modular system which is assembled with the use of three servo motors which are attached together with the use of C brackets. The center servo allows pitching motion up and down vertically whereas the servo motors connected to the caterpillar track modules on either side produce yaw motion which also allows the steering capability of the robot. In addition the use of linear tracks allow forwards and backwards movement.

Each track module has a comportment on top which acts as an enclosure for the electronically powered equipment to prevent increase in temperature and electrical currents. The track system allows more coverage over the uneven terrain in the fuel tank since the spars are at an elevation of 11mm from the wing skin, therefore the track allows steady movement over these terrains. The forward track module compartment holds the assembly for the linear telescopic mechanism which is able to extend and contract with the use of a stepper motor for slow controlled movement and the compartment houses the worm gear assembly for the linear actuation system so that it can rotate 360 degrees on its axis.

The robot navigation method is to be manual and will be teleoperated by an engineer in order to allow precise movement of the robot and to prevent the robot from colliding into the surfaces of the fuel tank. This again corresponds to the choice of material for the robot. Material is important to prevent friction which can lead to a spark of ignition, soft material such as rubber coating of components can be advantageous.

The power supply and communication source will be transmitted through a tether. The power supply distribution can also be carefully monitored to ensure that minimum amount of electric current is passing through to ensure that it is safe. The tether will also act as a manual way of retrieval incase the robot fails within the tank and can be pulled back to entry hole by engineer. This method does have its design flaws as it may snag between the components of the wing fuel tank, yet it is the most realistic option for retrieval if failure occurs. Lighting source for the robotic system is important since the conditions within a fuel tank are dark and there is the lack of natural light. LED lights can be placed either side of the track module to ensure that there is sufficient light and the camera can capture clear images. Additional sensors such as ultrasonic sensors, gas detectors and temperature sensors will all be part of the robotic structure to continuously monitor the conditions inside the fuel tank and provide relevant data back to the operator. The typical operating voltage of components such as DC motor, LED lighting modules and servo motors is between the limits of 5V- 12V. This proposed robotic system requires a tether therefore a CAT5 ethernet cable is one way to provide both a power and communication supply with up to 24W-25.5W power intake through the tether.

Onboard Manipulator Design

For the onboard manipulator several types of linear actuator mechanisms were analyzed to perceive which one would be the most suitable for the confined spaces. It was decided that a prismatic joint telescopic mechanism was the most appropriate design to choose. This being so that the design is compact and leaves enough room between the ceiling of the wing skin and manipulator in order to prevent unwanted contact between the robot and wing skin. The overall height of the robotic system has to be very well contained to prevent friction against wing skin. The manipulator will be powered with the use of a stepper motor for more control of movement in the confined spaces. The prismatic configuration is preferred as it allows minimal movement and will be assembled with a pulley system. The following section provides an overview of the robot design illustrated in CAD software CATIA V5.

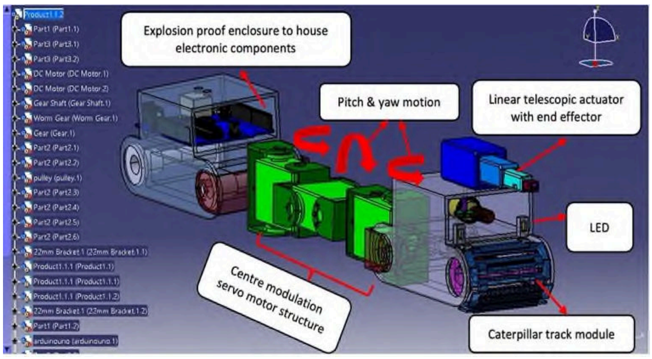

Figure 8.CATIA CAD model concept of robotic system

Digital Mockup of Proposed Mobile Robot

This section shows the digital mockup of the basic robotic system design. Figure 8 illustrates an overview of the robot system highlighting key components. Two caterpillar track modules, which also have safety explosion proof enclosures on top to house electronic components are attached to either side of the central modulation system which is constructed of three servo motors. On top of one of the track modules is also the linear telescopic actuator which will have the capability to hold an end effector or camera and extend and retract into the narrower areas.

Figure 9 shows a snapshot of the digital mockup of the robot entering the fuel tank from the access entry hole on the top of the wing. It shows the bending pitch motion of the servo motor revolute joint which allows the robot to easily enter the access hole.

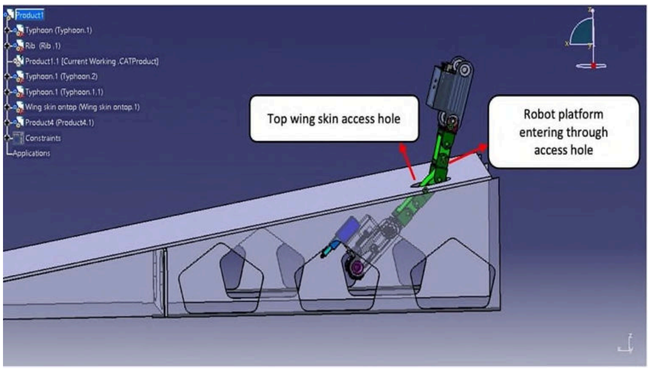

Figure 9.Robot position at entry access hole from top of wing skin

Figure 10 displays a snapshot of the digital mockup simulation of the robot system within the wing box. The robot simulates the linear telescopic actuator extending into the narrow space between the rib structure, which the robot platform itself would not have the proficiency to enter. This demonstrates the purpose of the actuator.

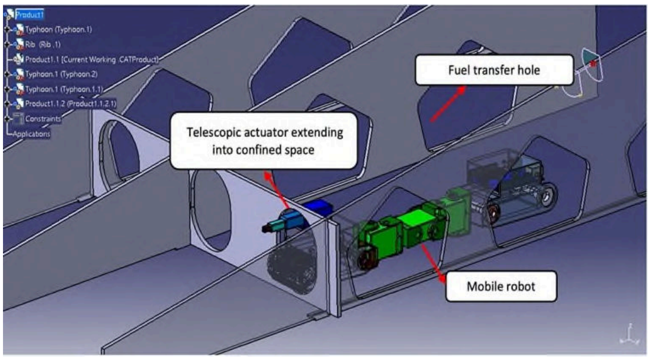

Figure 10.Linear telescopic mechanism extended through rib hole

Figure 11 shows the first test rig design of the typhoon wing box including the fuel transfer hole structure which has been constructed of carboard. An initial prototype of the robot chassis structure has been developed with the use of 3D printing. An Ultrasonic Sensor (UT) has been fixed onto the robot along with 2 LED light nodes and servo motors for experimental tests. The model represents how the robotic system would appear like within the test rig. This initial model will be used as a foundation and will be further developed to consist of realistic structures such as fuel conduits and wiring. The test rig will be used to conduct the experimental validation tests of the final robot.

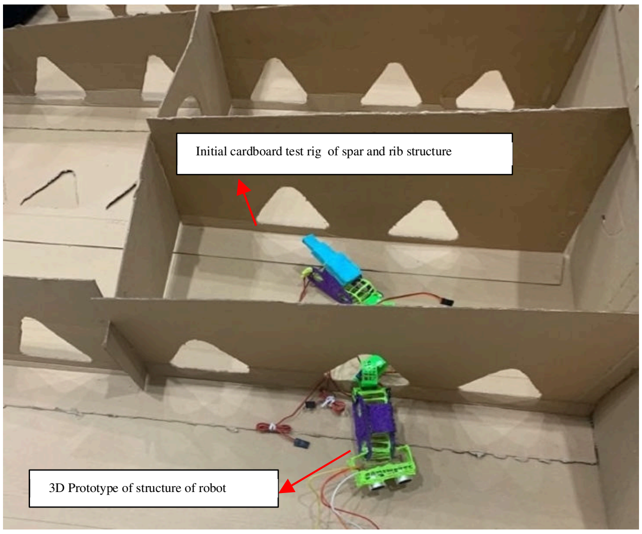

Figure 11 Basic structure prototype of robot in test rig

Table 2 illustrates the approximate dimensions of the robot chassis structure. The structure of the robot should not surpass these dimensional constraints. The overall length of the robotic system may be adjusted according to whether it may be longer or shorter however the height and width should remain fixed and not exceed 55mm. The length of the robot should be kept to a minimum so that it does not become obstructed in between structures which may also pose retrieval implications in case of a failure.

Table 2 Approximate dimensions of robotic chassis structure

Part Specification	Length (mm)		Height (mm)	Width (mm)	
1. Track Module	60 - 80		45 - 50	40 - 50	
2. Single Servo Motor Module	30 - 40		20 - 30	15 – 20	
3. C Bracket small	12 -15		22 - 25	12	
4. C Bracket large	12 - 15		26 - 28	12	
4. Telescopic Mechanism	Extend 60 - 90	Retract 30 - 40	15 - 18	Large section 30 - 40	Small section 10 - 20

In order to validate the robotic system design and ensure that it can successfully fulfill the requirements, several tests will be completed. These are briefly touched upon in the validation test of physical prototype section.

Validation Tests for Physical Prototype

Recent work has been introduced focusing on developing an architecture for verification and validation process particularly for robotic system design. Several models are integrated together each focusing on a specific set of requirements [18]. Within the architecture there are four models:

- An interaction model used to capture modes and preferences in user interaction. It primarily focuses on what information is provided by the operator to explain the robot's actions. In this particular case the robot will be controlled by the operator therefore, focusing on how effectively will the robotic system be able to adhere to the operators commands and conduct given instructions.
- A self-model, wherein the robot has a dynamic description of the (expected) behaviour of its own system components; robot arms, sensors, control systems, actuators, process tooling, power supplies, or planning systems. For each one of these subsystems there would be a formal description of the expected behaviour that the agent can use to monitor the various subsystems.
- A task model, capturing the set of tasks the robot must undertake for example inspection.
- A safety model, capturing the safety considerations identified in initial certification. The safety model in particular is required to cover how the system is operating, what are the safety requirements of the operational environment it is encountering and what responses is the system conducting. For this particular case the hazardous nature of the fuel tank has to be taken into great consideration and set requirements of how the robotic system should manoeuvre within this space, taking into consideration collision avoidance aspects.

Formal verification of the robotic system is to be completed with the application of extensive simulation testing as the system must inhabit the real-world, hence extensively test its behaviour, in all the above aspects, in more realistic environments. Once this is completed experimental test rigs can be developed to test the robot in an actual physical environment.

Discussion

The aim of this paper is to evaluate the current procedure of fuel tank inspection, highlighting the implications and risks imposed by the fuel tank environment. The research focuses on how the implementation of robotics can introduce numerous advantages. Proposals of current robotic systems have been evaluated and a critical review was completed assessing these systems. With the basis of this review a concept of a robotic system design is shown, primarily focusing on mobility of the system that would be the most suitable for entering the confined spaces of the fuel tank. Throughout the initial design phase and concept development it is clear that the research is multi-layered which involves several areas of design that are required to be carefully articulated in order to develop a successful operating robot for the harsh conditions.

On the basis of the engineering design methodology the initial stages were to highlight the key requirements of the project and to develop a design concept that would be the most appropriate before physical prototyping of the system. Various methods of mobility were evaluated including current proposals of robot locomotion of robot inspection for aircraft fuel tank inspection. The proposed concept meets the requirement of the robot having the capability of covering majority of the surface areas of the fuel tank.

The key findings from the work illustrated so far highlights many of the challenging aspects when developing a robust robot chassis and locomotion method for a hazardous environment. Apart from design of the robot chassis the design of the electrical system has to carefully constructed to fit within the small chassis of the robot yet be intrinsically safe. This also depends on the material selection of the robot since the build material of the robot will have to be able to withstand the corrosive substances of the fuel tank and keep the electrical energy intact. All these aspects tie together and is challenging to successfully implement all of these key characteristics together into a small sized robotic system. Developing a robotic system that is capable to maneuver within constricted spaces is an important design challenge to achieve which requires flexibility in the robot chassis. Figure 8 illustrates the telescopic mechanism which is described as a linear actuator that fits the purpose to access the confined spaces, however it is a rigid structure and cannot bend around sharp corners. This is one of the key design challenges that has been highlighted to further accomplish. The development of digital mockup and simulations will be able to highlight the behaviour of the robotic system visually for further design modification.

The paper has illustrated a step by step approach of developing an innovative locomotion design. The requirements developed for this project have assisted in fabricating an efficient locomotion method. The key findings behind this project are that there are several areas that need to be evaluated in regards to the design of the robot in an challenging environment. Fuel tank inspection has always been a challenging task in both large and small aircraft and detecting areas that contain defects always requires precise methods of inspection. The purpose of this project is to eliminate challenging procedures and exposure of toxic substances during of fuel tank inspection.

Conclusions

Aircraft fuel tank inspection is a challenging task especially when conducting inspection in confined spaces. The environment of the fuel tank is detrimental to ones wellbeing, if health and safety regulations are not followed correctly. The exposure of toxic vapor from jet fuel and lack of oxygen within the tank poses high risk and likelihood of explosion if intrinsically safe tools are not used during inspection tasks. In this paper an over view of current manual inspection tasks are highlighted and the difficulties imposed by the environment. The benefits of introducing robotic systems to assist with inspection tasks has been discussed along with current examples of robotic systems proposed for fuel tank inspection in literature research. The principal focus of this paper is the development of a suitable locomotion method of the robot in order for it to access confined spaces. This has been presented through the use of the engineering design methodology. A chosen design has been developed and illustrated through the use of CAD models. Further work in physical prototyping will be continued after this paper.

The key purpose behind the development of a mobile robot is so that it has the capability to cover majority of the wing box surface area. The mobile robot platform is able to access the large spaces of the fuel tank and with the camera on board it is able to capture images and videos in real time, which achieves the requirement of the robot system to conduct inspection in the fuel tank. However, by combining this with a manipulator or remote visual inspection tool onboard the robot gives the system an additional purpose to cover more areas of the fuel tank which the mobile platform will not be able to fully achieve. The onboard manipulator will be able to access the confined spaces of the fuel tank. Therefore both the mobile platform and manipulate serve a valuable purpose and can depend on each other. The combination of locomotion method which is both flexible and rigid in some aspects makes this robot suitable for multipurpose usage.

It also allows room for the addition of more sensors and end effectors. The impact of this work has great potential as it will assist engineers with inspection tasks that are hazardous to one's health, in which the physical health of an engineer outweighs the application of a robotic system in the toxic environment. However, engineers will still be required to teleoperate the robotic system and to monitor the conditions of the fuel tank whilst the robotic system carries out the inspection tasks.

The project is a multifaceted project which involves vigorous experimental validation of each characteristic of the robotic system from the electrical components to material testing in a developed test rig environment to ensure that it is suitable to be placed in the fuel tank.

Recommendations and Further Work

The physical scale of the robot is the most crucial design parameter as it is the foundation to hold the subsystem components within the limited dimensions of the robot chassis. This includes sensors, power supply source, lighting sources, camera and additional end effectors if needed. For small robots especially, there are many constraints due to the fact that all the design requirements are obligatory to be met without overloading the robot body with electrical and mechanical components. However with evolving technology, smaller sized sensors are becoming readily available which have a lower payload and will be the most appropriate to use for this particular research.

The second area of focus for further work will be the selection of electrical components to ensure that they meet the requirements to be intrinsically safe and incapable of releasing enough energy that can lead to an explosion within the fuel tank. Some components may meet the requirements to be intrinsically safe whereas some components may not. Components that are not intrinsically safe will need to be enclosed in a high strength container to prevent unwanted energy release. This design concept of developing an enclosure will be configured with the use of the hazardous environment electrical component standards. The Flash Point (FP) limit and Lower Flammability Limit (LFL) will be essential in order to select the right components.

The current design of the manipulator is presented to be a linear telescopic mechanism which is able to extend and retract into confined spaces. Attached to the end of the actuator would be an end effector for example a CCD camera module or a gripper. There are several advantages and disadvantages to this method with the first advantage that the mechanism can somewhat reach into the tight spaces however there are some design restrictions when it comes to this proposed methods. The proposed concept is based on rigid design and will mean that the actuator will be incapable of creating bending movements like that of a continuum arm since there is a lack of flexibility. One of the major recommendations and variation of the telescopic actuator would be that it can be designed to have greater flexibility similar to a borescope. Another alternative can be by introducing soft material application such as soft robotics which is a growing topic and can be adapted for this particular use case and can be developed to grow and expand into the confined spaces.

Materials or other parts of the robot need to be carefully selected. The use of rubber caterpillar tracks is suitable for the fuel tank environment as it produces less friction and less slippage. For the shell of the track module appropriate material will be required to cover it such as soft material so that the robot body itself does not damage the components of the fuel tank since collision between the robot and structure in the wing is inevitable. For the explosion proof enclosure, high strength steel would be a suitable choice as it will have the capability to withstand the corrosive substance and harmful vapor of the tank.

Apart from the physical enhancements of the robotic system. The robot can be further developed for other application purposes such as NDI, with the addition of non-destructive sensors to detect any presence of hidden corrosion. A varity of end effectors such as a gripper to pick up objects can be developed and assembled to the manipulator. The manipulator can be enhanced further for conducting advanced tasks such as repair work.

Recommendations based on current work have been proposed and briefly discussed. The next stages of research involve the completion of the following tasks. A physical prototype to be assembled incorporating both the electrical and mechanical components. This includes the combination of off the shelf electrical components such as motors, LED lights and 3D printed components of the robot chassis. Once the physical prototype is assembled, the prototype will be tested in a rig mockup of a wing fuel tank. Validation tests of the robot design will be completed in accordance to the project requirements. These tests will be repeated until sufficient amount of results are collected highlighting key findings. Simultaneously, digital mockup in CATIA V5 will be constructed along with basic simulations of the robotic system to evaluate the characteristics of the robot and analyse this data with the physical experimental results.

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