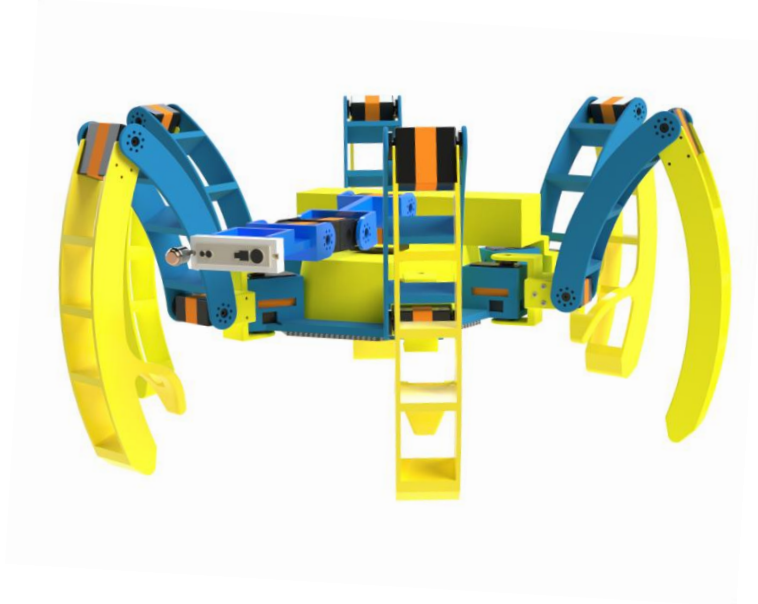


S.P.I.D.E.R. Surveying Platform and Inspection Device for Enclosed Regions



Team Members: All Senior Mechanical Engineers



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Mechanical Structure



Jonathon Rames
Mechatronics



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Systems



Mckenna DuFrene
Safety


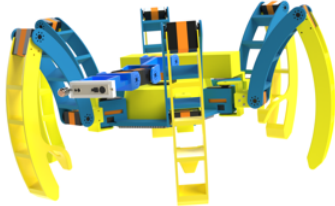
Faculty Advisor: Dr. Todd Letcher
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A handwritten signature in black ink that reads "Todd Letcher".



**SOUTH DAKOTA
STATE UNIVERSITY**

Quad Chart

S.P.I.D.E.R. <i>Surveying Platform and Inspection Device for Enclosed Regions</i>		
Project Summary: <ul style="list-style-type: none">• Robotic Fuel Tank Inspections• Develop a hexapod robot that can navigate the fuel tank of a commercial airplane including climbing over ribs and use visual / NDI inspection <u>in order to</u> limit human exposure to fuel vapors and dangerously tight spaces.	Project Image: 	
Team Composition/Roles: <p>Senior Design Project</p> <ul style="list-style-type: none">• Charlie Hartman<ul style="list-style-type: none">• Mechanical Structure Engineer• Jon Rames<ul style="list-style-type: none">• Mechatronics Engineer• Madyson Wantoch<ul style="list-style-type: none">• Systems Engineer• Mckenna DuFrene<ul style="list-style-type: none">• Safety Engineer	Proposed deployment timeline: <ul style="list-style-type: none">• Timeline for deployment by 2035 or sooner<ul style="list-style-type: none">• 2026<ul style="list-style-type: none">• Preliminary Design and 1st Prototype• 2027<ul style="list-style-type: none">• Relevant Environment Testing• 2028<ul style="list-style-type: none">• Begin Process for FAA Approval and Advertisement• 2029-2034<ul style="list-style-type: none">• Continue FAA Approval Process and Enact Relevant Changes• 2035<ul style="list-style-type: none">• Official Implementation	

Abstract

Aircraft fuel tank inspections are one of the most hazardous, physically demanding, and toxic “dirty jobs” in the aviation industry. Currently, maintenance technicians must wait 24 hours for vapor venting before performing “tank dives” into claustrophobic, chemically volatile, and ergonomically punishing environments. This process not only risks acute physical injury and long-term neurological damage to personnel, but it also imposes significant operational downtime on global fleets. Airlines can lose on the order of \$100,000 per aircraft per day, when grounded. For a fleet of 800 aircraft, that translates to about \$8,000,000 in annual losses, highlighting the massive economic impact tied to inspection delays.

S.P.I.D.E.R. (Surveying Platform and Inspection Device for Enclosed Regions), a bio-inspired hexapod robotic system engineered to redefine the boundaries of aviation safety and efficiency. Built with advanced carbon-fiber-reinforced PEEK and static-dissipative elastomers, S.P.I.D.E.R. is designed for safety in ATEX Zone 0 environments and can be deployed immediately after fuel drainage, reclaiming the “lost 24 hours” typically required before human entry. Utilizing a high-torque tripod gait and a multi-degree-of-freedom non-destructive inspection arm, the platform navigates complex internal geometries to deliver real-time, high-definition 360° telemetry to technicians outside the tank. By eliminating the need for human entry, in many cases, and accelerating inspection timelines, S.P.I.D.E.R. not only improves safety but also offers a strong return on investment, with projected savings of approximately \$2,000,000 per year through reduced downtime and increased fleet availability. This paper expands upon climbing navigation, mechatronics design, future implementation of AI through reinforcement learning, claw design, material encasement, tether-less communication, steps to implementation, and the economic impact of S.P.I.D.E.R.

Situation Assessment

Fuel tank inspection remains one of the most physically/mentally demanding and hazardous tasks in aircraft maintenance. To better understand this challenge, our team conducted interviews with more than 20 professionals in the aircraft maintenance industry. Fuel tank entry was consistently stated as an undesirable, yet necessary procedure, due to confined spaces, restricted mobility, and the presence of lingering fuel vapors. Technicians must maneuver through small access ports and navigate multiple internal compartments, creating a work environment that is both uncomfortable and potentially dangerous.



Figure 1 – Tight Enclosed Workspace [4]

Current inspection procedures require trained aircraft maintenance technicians to physically enter the drained fuel tank after extensive preparation. All fuel must be removed, and the tank atmosphere cycled for approximately 6-24 hours [1, 2, 3] before entry is considered safe. Even under these controlled conditions, technicians face significant ergonomic strain and safety risks within tight, enclosed structures – see Figure 1.

The AMFA, Aircraft Mechanics Fraternity Association, was a helpful source of information. The National Safety Standards Director and former Southwest Avionics Technician, Tom Wiggins, one of our interviewees, told a story of one of his tank dives. In this instance, he became trapped when his belt snagged on an interior feature while exiting a tank port, leading to panic, loss of body control, and near injury before he was freed with assistance from a colleague [T. Wiggins, (AMFA National Safety Standards Director, Former AMT at Southwest), personal communication, October 29th, 2025]. Incidents such as this highlight the inherent risks associated with confined-space fuel tank inspections.

Beyond immediate physical hazards, exposure to jet fuel vapors presents potential long-term health concerns. Experimental research has demonstrated significant immunological impacts in exposed test subjects, while human studies suggest possible neurological effects linked to certain jet fuel exposures. Although the complete range of long-term health outcomes remains uncertain, evidence indicates occupational risk for maintenance personnel regularly performing fuel tank inspections [3, 5]. The Agency for Toxic Substances and Disease Registry, under the U.S. Department of Health and Human Services, published a health statement regarding jet fuel exposure. They stated, “The health effects of JP-5, JP-8, and Jet A fuels depend on how much of these fuels you are exposed to and for how long. We know little about the human health effects caused by JP-5, JP-8, or Jet A fuels. A few studies of military personnel have provided evidence that JP-8 can affect the nervous system. Some of the effects that have been observed in humans include changes in reaction time and other tests of neurological function” [6].

Aircraft maintenance technicians play a critical role in ensuring the safety of air travel for hundreds of thousands of passengers each day. Reducing the time these professionals spend in hazardous, confined, and chemically exposed environments is therefore both a safety priority and an operational opportunity. By targeting improvements in fuel tank inspection methods, this project aims to enhance technician safety, decrease maintenance burden, and improve overall efficiency within heavy maintenance operations.

Though specific standards do vary from airline to airline, in the case of an Airbus A320, inspections are completed every 6 to 12 years. Central, and relevant, tasks associated with fuel tanks are the General Visual Inspections (GVI) which include: GVI for Electrical Wiring Interconnection System (EWIS), GVI of internal tank and wiring and probe attachments, and GVI for EWIS of vent surge tank, among others [1].

Airlines lose about \$100,000 per day for each airplane that is grounded. On average, fuel tank inspections for all airlines happen at every “heavy check,” which occur every 6 to 10 years. Before fuel tanks can be inspected, they must be air-purged from any fuel vapors inside. This is done by blowing filtered air into the tank until the oxygen levels meet safety standards [1]. Air-purging of the fuel tank takes a minimum of 6 hours before gas concentration levels are even initially tested. Gas concentration must be less than 10% of the lower explosion limit, and oxygen levels must be between 18% and 21%, and the approximate human inspection time once inside the fuel tank is around 8 hours for one aircraft [1]. Other

sources indicate that air-purging can take up to 24 hours before anyone is allowed inside to carry out inspections [2, 3]. Every hour that an airplane is grounded, costs the airline additional money. SPIDER will reduce the time an aircraft is grounded for fuel tank inspections as it can be deployed as the tank is still fumigated. This will save an airline an average of \$2,000,000 every year across its fleet of aircraft.

Use Case and Proposed Solution

To reduce the time aircraft maintenance personnel must spend inside commercial aircraft fuel tanks, the team proposes the Surveying Platform and Inspection Device for Enclosed Regions (S.P.I.D.E.R.), a hexapod robotic system capable of performing fuel tank inspections and supporting nondestructive inspection (NDI) operations. A hexapod robot, or a robot with six legs, is a versatile design for this application as it provides not only effective mobility but also stability. S.P.I.D.E.R. will always have three points of contact with the ground while still maneuvering efficiently.

Because S.P.I.D.E.R. is not subject to the physiological hazards associated with confined spaces or fuel vapor exposure, the system can be deployed inside a fuel tank prior to conditions being safe for human entry (before the 6 to 24-hour period allowing the tank to air out has ended). This capability enables inspections to begin earlier in the maintenance process, reducing aircraft downtime and improving operational efficiency. After the tank atmosphere is cleared for safe entry, an aircraft maintenance technician can enter, but will only have to enter if the robotic inspection shows concerning information or can confirm problems. If no defects are detected, human entry may be avoided entirely. S.P.I.D.E.R. may also allow for more frequent inspections, allowing for early identification of anomalies before the problems become bigger or catastrophic. In addition, repeated robotic inspections create opportunities for long-term structural health monitoring and predictive maintenance across airline fleets.

S.P.I.D.E.R. will be operated by certified aircraft maintenance technicians trained in NDI methods. Real-time camera feeds and sensor data will be transmitted to the technician for analysis and verification of fuel tank integrity. The robotic platform will include a maneuverable imaging system capable of 360-degree articulation, enabling inspection of structural features on the tank floor, ceiling, and internal webs while navigating complex internal geometries. The NDI operator will have maneuverability and vision similar to what would be experienced by the technician if they were physically inside the fuel tank.

To maximize the area S.P.I.D.E.R. can inspect, a smaller “SPIDERling” could be developed utilizing the same platforms as the main robot with the femur and tibia scaled down to fit in the narrow wingtip areas of the fuel tank. These areas lack the high rib openings, making it easier to traverse without requiring longer legs. This may enable inspections of areas that even human technicians cannot do.

This capability directly addresses inspection requirements associated with regulatory airworthiness directives issued by aviation authorities such as the FAA and EASA. Representative examples include visual and eddy-current inspections of center fuel tank structural webs on Boeing 777 aircraft, wiring and structural inspections within Boeing 767 center wing tanks, and combined visual and high-frequency eddy-current inspections in Boeing 737 Next Generation and 737 MAX fuel tanks [7]. By enabling inspection during tank purging and prior to human entry, S.P.I.D.E.R. has the potential to shorten grounding durations and reduce maintenance burden for airline operators.

Concept of Operations

A primary technical constraint on the proposed system is operation within a hazardous fuel-vapor environment. Commercial aircraft fuel tanks are commonly treated as equivalent to ATEX Zone 0 [8], defined as a location in which an explosive atmosphere consisting of a mixture of air with flammable gas, vapor, or mist is present continuously for extended periods. Because S.P.I.D.E.R. is intended to enter a drained fuel tank while vapor concentrations are still being reduced through purging, all electrical, mechanical, and material design choices must prevent ignition under worst-case conditions. Although current regulatory frameworks prohibit conventional electronic systems in Zone 0 environments, this

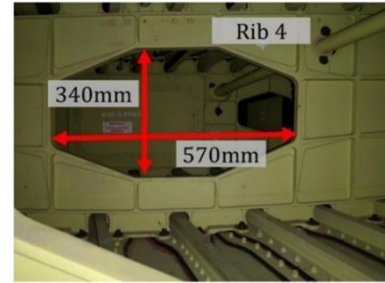


Figure 2 – Airbus A320 wing fuel tank rib opening [1]

project establishes a design pathway toward intrinsically safe robotic inspection technologies suitable for future certification.

To ensure international relevance, the design references both European ATEX/IECEx guidance and U.S. hazardous-location standards. These two standards were also suggested by Matthew Heiser, whom we interviewed [M. Heiser, (AMFA Local 32 Secretary, Former AMT (Aviation Maintenance Technician) at Southwest), personal communication, November 3rd, 2025]. The U.S. Class I, Division 1 classification similarly describes environments in which ignitable concentrations of flammable vapors may exist during normal operation or maintenance. The analysis focuses on Jet A and Jet A-1 fuels, which are operationally equivalent for this purpose, aside from freezing-point differences. These fuels exhibit lower volatility than gasoline-class fuels and possess flash points near 100 °F and auto-ignition temperatures of 435–450°F. Based on hazardous-location temperature-class guidance, this corresponds to a permissible electrical equipment surface temperature consistent with T2D classification, informing allowable thermal limits for onboard components. More information about ATEX ratings for electronics is available in the Appendix.

Environmental conditions inside recently drained tanks are also bounded. Regulatory guidance indicates that an unheated tank equilibrates closely with ambient air temperature. Because inspections are typically conducted in controlled hangar environments below 100°F, S.P.I.D.E.R. is designed for reliable operation within this temperature range, providing adequate thermal margin relative to ignition thresholds and component limits.

Materials and Electrostatic Safety - Update

This section has been updated since the proposal. Material selection for the robot body is critical to minimize ignition risk from electrostatic discharge or triboelectric interaction with the aluminum fuel-tank structure. Candidate materials included aluminum, carbon-fiber composite, and carbon-fiber-reinforced PEEK [9]. Evaluation criteria included triboelectric interaction with aluminum, density and resulting system mass, surface resistivity relative to ATEX requirements ($\leq 10^9 \Omega$), Thermal capability, and cost.

Carbon-fiber-reinforced PEEK satisfied resistivity limits, reduced density, maintained high continuous-use temperature capability (~ 480 °F), and offered favorable cost in bulk production [10]. Additionally, PEEK has excellent chemical resistance [11], and it is among the strongest thermoplastics in terms of mechanical strength and high fatigue life [12]. From these evaluations, reinforced PEEK was selected as the primary material for structure and hardware.

The contact surfaces on the feet and climbing sections of the legs require material that provides reliable slip resistance while remaining safe for use inside aircraft fuel tanks. Suitable materials must minimize static charge accumulation and triboelectric interaction while maintaining adequate traction on potentially oily aluminum surfaces. Several industry-qualified options exist for hazardous environments with similar electrostatic and chemical constraints such as static-dissipative NBR, acrylonitrile butadiene, rubber. One representative example is static-dissipative, oil-resistant Buna-N rubber sheet commonly available as an off the shelf purchase at many industrial suppliers, which offers controlled surface resistivity in the range of 10^6 – $10^9 \Omega/\text{sq}$, preventing hazardous charge accumulation, and is therefore compatible with electrostatic safety requirements for fuel-tank inspection applications.

For the purpose of safety, total encasement of motors, wiring, and electronics with the aforementioned materials is recommended. Additionally, separate encasement of the battery away from the onboard computer and servo controller is suggested. The body of S.P.I.D.E.R. containing these essential components and the joint connections will be bolted in accordance with ATEX Zone 0 regulations regarding preventing “ignition even when two independent safety barriers fail simultaneously” [13]. This will decrease material vibrations and friction and avoid fault conditions like misalignment of parts that could cause S.P.I.D.E.R. to trip or otherwise loosen.

Detailed Mechatronics Design - Update

This section has been updated since the proposal. S.P.I.D.E.R.’s locomotion system is driven by high-torque servo motors capable of supporting both walking and climbing maneuvers through structural rib openings inside aircraft fuel tanks. Required motor torque is estimated by multiplying the total robot weight by the effective femur length and dividing by two to approximate the load supported during a two-

leg pull-over condition, with a safety factor. For the prototype mass of 5.1kg and femur length of 15.3cm, the calculated minimum torque requirement is approximately 40 kg*cm, establishing the lower bound for actuator size. In the current prototype, off-the-shelf motors are utilized, however, in the future, custom build servos or encoded BLDCs may be used.

Servo coordination is managed using a serial bus servo architecture controlled by a dedicated bus-compatible controller. This configuration simplifies wiring, enables synchronized motion control, and improves system reliability compared with traditional point-to-point PWM control. The selected controller provides a streamlined interface for configuration, feedback, and coordinated gait execution.

For S.P.I.D.E.R. to obtain data on its position relative to the ground, an inertial mass unit (IMU) will provide data such as pitch, yaw and roll of the base plate. This is a crucial sensor to the implementation of AI so that S.P.I.D.E.R. can know how it is positioned and maneuver more efficiently.

To process onboard sensing, imaging, and communication tasks, an embedded energy efficient edge-computing platform is required. After evaluating lightweight computing options, including Raspberry Pi and embedded AI platforms from NVIDIA, the Jetson Orin Nano was selected for the prototype for its favorable balance of computational performance, power efficiency, and size. Continued advances in embedded computing may enable higher-performance drop-in replacements by the anticipated deployment timeline that may be lighter weight and less volume, and also more energy efficient, allowing for smaller batteries.

Software integration is built on the Robot Operating System (ROS) framework to manage inter-process communication, motion control, sensing, and operator interfaces within a modular architecture. Simulation and autonomy development are supported through NVIDIA Isaac simulation environments, enabling physics-based virtual testing, control validation, and reinforcement-learning-based mobility optimization prior to hardware deployment. Expanded simulation results and autonomy performance metrics are planned for inclusion in future development phases.

In these development phases we would work closely with airlines and aircraft manufacturers to create a detailed Omniverse Digital Twin, replicating the inside of these complex fuel tanks virtually. This environment can be thought of as a virtual space where S.P.I.D.E.R. will be trained in how to efficiently navigate the fuel tank using reinforcement learning. Once satisfied with the behavior during the simulations, the models can be implemented seamlessly with the current Nvidia + ROS architecture to enable efficient navigation of fuel tanks. Fuel tanks currently are one of the few systems lacking digital twins [1]. S.P.I.D.E.R. will be able to fill this gap and record footage of inspection for future reference and comparison to better monitor the health of the fuel tank.

Thermal safety is monitored using onboard temperature sensors positioned near critical heat-generating components, including the battery, servo controller, and embedded computer. If measured temperatures exceed defined safe operating thresholds, the control system will automatically transition the robot into a protected idle or shutdown state to prevent overheating and eliminate potential ignition risk. The servo motors also track their own junction temperature through embedded sensors. Therefore, if the temperature of a servo motor exceeds its threshold, the safety features of the system will take over.

Reliable wireless communication is required for teleoperation and data transmission. Signal strength will be continuously monitored to ensure sufficient connectivity for safe navigation and exit from the fuel tank. Loss of communication represents a critical hazard condition, particularly during climbing maneuvers, and therefore informs both fail-safe behavioral design and retrieval planning. Our initial prototype will be operating outside of a real fuel tank using a wooden-built structure, so the same signal blockers may not exist. As we learn more about the signal blockers and signal transmission problems, we anticipate developing a signal repeater inside the fuel tank to allow S.P.I.D.E.R. to progress farther into the tank. The signal repeater will be placed inside the fuel tank by the hexapod as it moves into and through the fuel tank, then picked up on the way back to the entrance. This adds another layer of complexity to robotic operations, but similar approaches have been successfully employed in environments where signal transmission is challenging, such as mines and submarines.

To power S.P.I.D.E.R. inside of the fuel tank, a 14 Ah capacity battery has been chosen to allow an operating time of 2 hours inside of the tank at a time. A detailed discussion of these calculations is

provided in the Appendix. We chose 2 hours as it still allows for a lightweight design of the robot while still allowing enough time for inspections inside of the tank. When S.P.I.D.E.R. starts running low on power, it can return to the outside opening to swap out for fresh batteries. For the prototype, a 3s LiPo battery was chosen to power the Jetson and servos. However, due to the extreme power spikes from the servos creating ‘dirty’ power, there were issues with brownouts in the Jetson, causing a disconnection with the controller. Moving forward, the team plans to power the Jetson and servos separately to prevent any chance of a brownout inside of the tank.

Intrinsic Safety Constraints and Component Certification Gaps

Another key limitation of operation inside aircraft fuel tanks is the presence of fuel vapors that are extremely sensitive to potential ignition sources. While certain industrial sensors, wiring methods, and low-power instrumentation are currently certified for ATEX Zone 0 environments, many components required for a mobile robotic platform, such as high-torque electric actuators, onboard computing hardware, rechargeable battery systems, and high-bandwidth wireless communication devices, do not yet possess safety certification. This gap represents a primary barrier to immediate deployment. However, continued advancement in safe electronics, energy-limited power architectures, and sealed actuator technologies suggests a feasible pathway toward compliant robotic subsystems within several years, especially if a need for these components has been identified and an application exists for the components. By targeting a development horizon extending to 2035, it is reasonable to anticipate that certified components will emerge through broader industrial demand. Should such components remain unavailable, a focused engineering effort could pursue custom intrinsically safe designs followed by formal testing and certification to enable safe robotic inspection within fuel-tank environments.

Mobility Design – Update

This section has been updated since the proposal. A hexapod configuration was selected to maximize stability on uneven internal tank geometry (see Figure 3 for the prototype CAD model). The locomotion strategy employs a tripod gait, similar to an ant or any other 6-legged insect, ensuring three simultaneous ground-contact points during walking to prevent tip-over. A dedicated climbing gait enables traversal across structural ribs and compartment openings, with mechanical hooks and textured contact surfaces providing secure engagement. During climbing maneuvers, such as through a tight passageway as shown in Figure 2, the robot maintains a minimum of three contact points to preserve static stability.

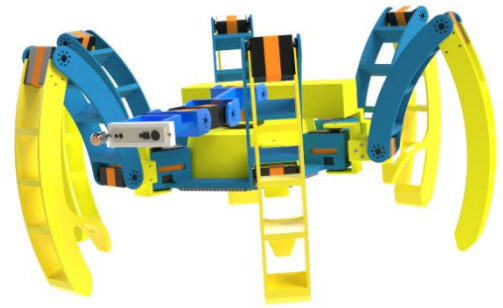


Figure 3. Prototype CAD Model

To increase the mobility and stability of S.P.I.D.E.R. during climbing gates a claw has been created at the end of the front and back legs. These claws provide additional leverage for S.P.I.D.E.R. while pulling itself through the ribs to improve its climbing ability.

Climbing Research - Update

This section is an update since the proposal. Currently, S.P.I.D.E.R. can comfortably climb 11 in. off the ground through an opening with 21.5 in of width and 13 in. of height. This was tested in a simulated environment with a wooden mockup of the rib opening from Figure 2. Reinforcement learning will be used to allow the machine to learn how to position itself to quickly and safely move through openings and over obstacles. Several functions have already

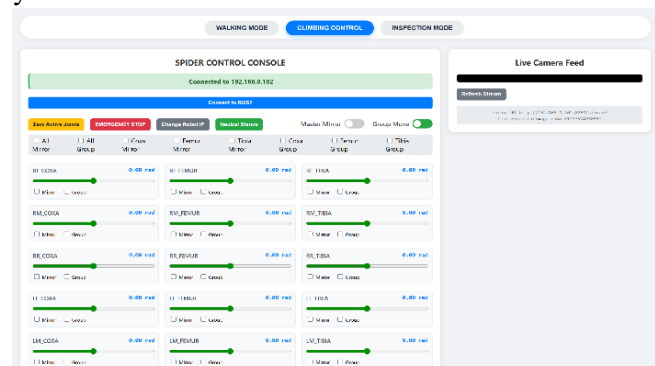
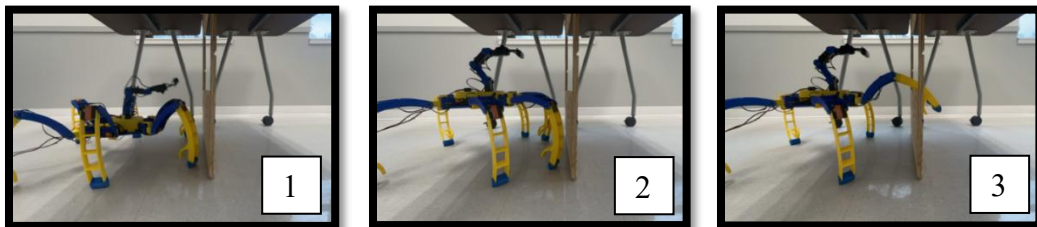


Figure 4. Web controller used for climbing

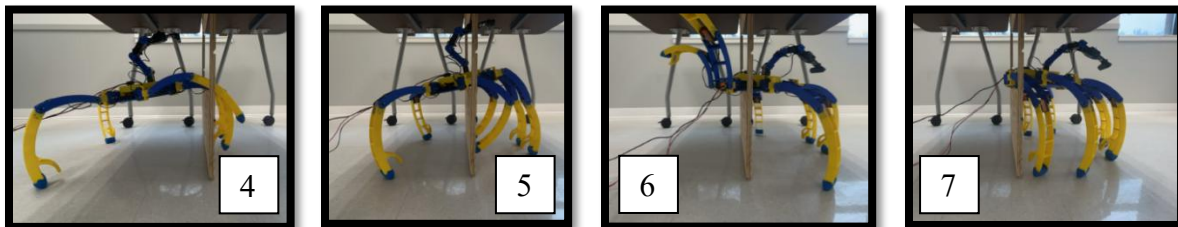
been created to simplify the control strategy for repetitive motions. One function that simplified the climbing gait was implementing a mirror function on the graphical interface. This allowed two or more body parts on opposite sides to move at the same time but mirrored. This reduced climbing time significantly, compared to fully human controlled joints. Additionally, a group functions was added to the controller, allowing selection of a combination of body parts to all move according to the input of one of the legs. One of the most important lessons from experimenting with climbing was the impact on the femur servos. The femur servos need to be stronger to prevent excessive buildup of thermal energy from nearing stall current when the robot reaches these unique positions required for getting through the opening, specifically for navigating higher openings. These servos frequently reach temperatures of 80°F when operating in a climate-controlled environment, so operating them in the hot atmosphere of a fuel tank will potentially cause problems for S.P.I.D.E.R. in the future. Another issue that appeared was the difficulty of pulling the last two legs through the opening. Further functions are being developed that would allow for a quadrupedal gait for the other four legs. This would properly distribute load to the servos, simplify the process, and decrease the overall time further.

The following screenshots were taken from a video of a single climbing attempt using the prototype that was developed over the last few months. The opening is 11 in. off the ground, and the size of the opening is 21.5 [W] in x 13 [H] in.

The general process that was developed was to approach the opening to within 1 inch of the wall (1). Next, the back four legs were spread out, and the entire height of the robot was raised (2). Next, the front legs were swung up in unison and down onto the bottom of the opening (3).



The two front legs pulled the robot forward (4), then the middle legs swung up to the opening, and the front legs are positioned as close as possible to the ground of the fuel tank (5). The robot tilted forward by lowering the front legs (6). The back legs were swung through the opening and repositioned with the other legs (7).



Sensing, Inspection, and Manipulation - Update

This section has been updated since the proposal. An articulated inspection arm mounted above the chassis carries the primary imaging system and an eddy-current nondestructive inspection probe (not seen in the CAD model). The arm provides multi-degree-of-freedom positioning and near-omnidirectional viewing coverage, enabling inspection of the tank floor and ceiling surfaces, structural ribs, webs and joints, and wiring, fasteners, and seal interfaces.

The selected RGB imaging system provides 1920 × 1080 resolution at 30 fps with an 80–85° diagonal field of view, supporting reliable detection of surface defects of about 2–3 mm based on pixel-density analysis at typical inspection distances. Real-time video and NDI data are transmitted to a certified aircraft maintenance technician for interpretation and airworthiness determination. As small camera technology continues to improve, new options for better resolution and low light capabilities will be

implemented as the robot continues to develop. In addition, AI capabilities will also improve, allowing for the robot to make determinations of areas where further inspection is needed.

The main NDI technique that S.P.I.D.E.R. will be using is eddy current. This method is currently widely used in the aircraft industry for detecting sub-surface defects within structural components of aircraft. For initial implementation, an AMT will evaluate the data sent from the eddy-current probe to identify any defects. Although eddy current technology is used in fuel tanks currently, it has never been used while fuel tanks are in the process of air purging. Testing would be required to validate the security of using eddy current before full air purging is complete. While currently there are no specific ATEX Zone 0 rated eddy-current probes, we plan to use and certify an off-the-shelf eddy current probe to achieve this rating on a robotic system.

The current prototype of S.P.I.D.E.R. has a maximum vertical inspection height of 32 inches with eddy-current inspection and 44 inches for visual inspection of cracks of 2 mm or more. For most areas of the tanks this height will be sufficient to carry out all the needed inspections. For areas, such as the main body tank, S.P.I.D.E.R. can leverage itself against walls, pipes, and other obstacles inside of the tank to reach areas that are difficult to reach. Limited information is openly available for fuel tank geometry and obstacles, but we are confident that S.P.I.D.E.R. either currently meets the full needs of inspection, or can be easily modified to accomplish a currently unknown geometry or obstacle.

Transmission of Signal and Data - Update

This section is an update since the proposal. S.P.I.D.E.R. needs free movement through the fuel tank, unrestricted by wires, not only for convenience, but also for safety. In order to have the greatest range of mobility, a tether for connection is undesirable. A Wi-Fi connection would allow S.P.I.D.E.R. to crawl around without the concern of a tether. We do not have access to an aircraft for testing, so a small, simulated environment was created. A test was designed to determine if a Wi-Fi connection could be maintained within an aircraft fuel tank. To achieve this, a box was lined with multiple layers of aluminum foil until a Wi-Fi signal was completely blocked when the box was completely enclosed. To test a Wi-Fi signal, a phone transmitting a Wi-Fi signal using its hotspot was placed inside the box and transmitted signal to a laptop outside the aluminum foil box. The signal strength was monitored on the laptop. Signal was lost when the aluminum foil box was closed, and signal was regained when the box was opened. Next, baffles were created and placed in the box to add more reflectivity to the signal. Under both described conditions, Wi-Fi connection was stable, with or without baffles when the opening existed. Further testing under real-life conditions is recommended.

Economics - Update

This section is an update since the proposal. Every time an airplane is grounded, the airline loses money. Not only do airlines have to pay parking and hangar fees, but they are also experiencing a loss of revenue. Over the 24-hour ventilation period, airlines can lose \$100,000 per day. For a fleet of 800 aircraft, having fuel tank inspections at a minimum of once every 10 years, \$8,000,000 is lost per year. S.P.I.D.E.R. would not have to wait to enter the fuel tank during this ventilation period. The goal is to create a contract with airlines for the service of fuel tank inspections. It is estimated that S.P.I.D.E.R. could get into and inspect the fuel tanks and be out in less time than it takes to vent out the fuel tanks. At a low estimation of a quarter reduction in the time the aircraft is grounded for inspection, S.P.I.D.E.R. could save airlines \$2,000,000 per year. With major airlines having fleets greater than 800 aircrafts, the cost savings could be even greater. The cost of producing the first prototype of S.P.I.D.E.R. was around \$1,000. The predicted cost of a full prototype, ATEX Zone 0 rated with eddy current, is around \$10,000.

Overview of Technology Application

This section has been updated since the proposal. S.P.I.D.E.R. is designed to integrate directly into existing commercial aircraft fuel-tank inspection workflows with minimal disruption to current maintenance practices, other than decreasing the amount of time required. The system is deployed after fuel drainage begins and may enter the tank during the purging phase, prior to conditions being safe for human entry. The robot performs visual and nondestructive inspection (NDI) surveys, transmitting real-time data

to a certified technician located outside the tank. Based on inspection results, maintenance personnel either prepare targeted repairs before entry or, when no defects are detected, avoid human tank entry entirely. This workflow reduces confined-space exposure while preserving current regulatory inspection authority and technician decision-making.

➤ Minimal Barriers to Adoption and Use:

S.P.I.D.E.R. is intentionally designed to align with established maintenance culture, certification structures, and operational expectations:

- Effectiveness: Provides earlier defect detection and full inspection of confined tank regions
- Simplicity: Operated through a familiar inspection interface with real-time video and NDI data
- Reliability: Hexapod stability, fail-safe shutdown logic, and health monitoring reduce risk
- Maintainability: Modular components enable rapid servicing using common tools and procedures
- User friendliness: Operated by already-certified NDI personnel, avoiding new workforce specialty
- Operational relevance: Preserves existing human inspection authority, documentation practices, and safety protocols.

Together, these factors minimize training burden, procedural change, and regulatory friction, key enablers of adoption in commercial aviation maintenance environments.

➤ Support System Needs and Technology Readiness Level (TRL):

Initial deployment requires:

- External operator workstation and control interface
- Certified power and charging infrastructure
- Data storage compatible with maintenance record systems
- Retrieval tools for contingency recovery

Current subsystem maturity corresponds to:

- Mobility platform: TRL 4–5 (validated in laboratory and relevant environments)
- Inspection sensing: TRL 5–6 (NDI sensing mature; robotic integration emerging)
- Intrinsic safety compliance: TRL 2–3 (conceptual to early prototype stage)

➤ Connectivity Constraints:

Fuel-tank interiors impose strict communication and power limitations:

- No GPS availability inside metallic tank structures
- Wireless signal attenuation through aluminum structure and confined geometry
- Battery-only operation due to intrinsic-safety and cable-management constraints
- Limited external network dependence, allowing offline operation within hangars

To address these constraints, S.P.I.D.E.R. relies on:

- Short-range, high-reliability wireless or tether-optional communication
- Onboard autonomy for safe halt/return behaviors during signal loss
- Energy-efficient compute and sensing to maximize mission duration

➤ Environmental Challenges:

Although inspections typically occur inside hangars, several adverse conditions must be considered:

- Residual fuel vapors and flammable atmospheres
- Low lighting and reflective metallic surfaces
- Temperature variation within unheated tanks
- Contaminants such as fuel residue, sealant, or moisture

S.P.I.D.E.R. mitigates these factors through intrinsic-safety design principles, integrated lighting and imaging optimization, temperature monitoring, and slip-resistant electrostatic-safe materials.

➤ Interoperability with Existing Ecosystems:

The system is designed for seamless compatibility with:

- NDI technician workflows and qualifications and existing inspection documentation records
- Standard aircraft maintenance scheduling and hangar operations
- Regulatory inspection authority and approval processes
- Conventional repair tooling and procedures

S.P.I.D.E.R. functions as an inspection enabler, not a replacement for certified personnel, ensuring organizational acceptance and regulatory continuity.

➤ Expected Improvement Over Existing Practices:

Compared with traditional human tank entry, S.P.I.D.E.R. is expected to deliver:

- Reduced confined-space exposure for maintenance personnel
- Earlier inspection start times during tank purging
- Shorter aircraft downtime and faster return to service
- Improved inspection coverage and repeatability
- Foundation for predictive maintenance using repeatable digital inspection data

Collectively, these improvements enhance safety, efficiency, and operational readiness while preserving the expertise and authority of aircraft maintenance professionals.

Technology Readiness Level (TRL) Maturation Roadmap

Current State – TRL 3 to 4

- Analytical proof of concept for robotic inspection in hazardous fuel-tank environments.
- Component-level demonstrations of mobility, sensing, and computation in laboratory settings.

Near-Term Advancement – TRL 5

- Integrated prototype validated in controlled confined-space environments.
- Demonstrated inspection capability and operator control outside hazardous atmospheres.

Mid-Term Advancement – TRL 6

- System demonstrated in representative metallic tank structures with realistic constraints.
- Verified safety behaviors, communication reliability, and inspection performance.

Pre-Operational Readiness – TRL 7

- Prototype demonstrated in operational maintenance environments under supervision.
- Evidence of reliability, maintainability, and measurable safety improvement.

Operational Readiness – TRL 8–9 (Post-2030 Path)

- Certified system performing routine inspections in commercial service.
- Documented operational benefit, safety improvement, and lifecycle sustainability.

Path to Deployment

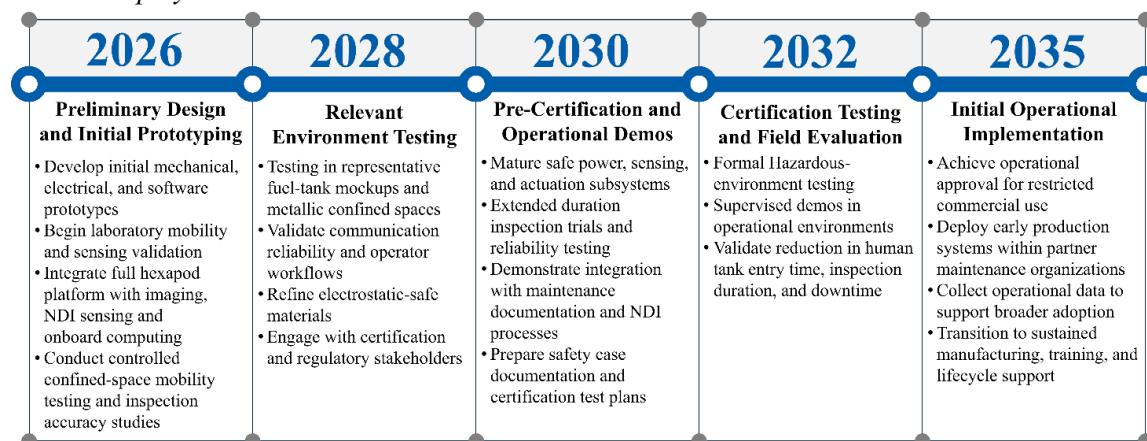


Figure 5. Timeline for Path to Deployment

Safety Case and Operational Justification

Hazard Reduction Strategy

The primary safety objective is reduction of human exposure to confined, fuel-vapor environments:

- Performing inspections before safe human entry conditions exist
- Enabling no-entry outcomes when defects are not detected
- Reducing time-in-tank when repairs are required
- Providing repeatable digital inspection records for decision support

Intrinsic Safety Philosophy

System design follows hazardous-environment engineering principles:

- Electrostatic-dissipative structural and contact materials
- Thermal monitoring with automatic shutdown
- Fail-safe loss-of-communication behavior

Operational Risk Balance

Traditional fuel-tank inspection requires:

- Confined-space human entry
- Direct vapor exposure
- Physical entrapment risk
- Extended aircraft downtime

Robotic pre-inspection shifts risk from human exposure to engineered system controls, which are certifiable and continuously improvable.

Expected Safety Outcome

Implementation is expected to produce:

- Significant reduction in confined-space entries
- Lower cumulative technician vapor exposure
- Fewer inspection-related injuries or near-miss events
- Improved maintenance planning and aircraft availability

Conclusions and Key Findings

S.P.I.D.E.R. represents a practical and innovative solution to one of the most hazardous, most disliked tasks, and inefficient procedures in modern aircraft maintenance – fuel tank inspection. By leveraging a bio-inspired hexapod platform, intrinsically safe material selection, and integrated visual and nondestructive inspection capabilities, the system directly addresses the key challenges identified in current fuel tank inspection practices. The ability to deploy during the purging phase, prior to safe human entry, fundamentally shifts the inspection timeline and allows maintenance operations to begin earlier, reducing overall aircraft downtime and associated economic losses of \$100,000 per day of a singular grounded aircraft. Modern airline fleets may be able to save nearly \$10M per year when used across their entire fleet. Besides being more cost efficient, removing or minimizing the need for human tank entry significantly reduces technician exposure to confined spaces, fuel vapors, and ergonomic strain, improving immediate and long-term safety and health, and just as importantly, increase job satisfaction for aircraft technicians.

Our experimental prototype validation of mobility, climbing performance, and sensing capabilities demonstrated that the core functions of the system are feasible, while the outlined path to deployment and TRL maturation provides a realistic roadmap toward eventual certification and industry adoption. Although challenges remain, particularly in testing in order to achieve ATEX Zone 0 compliant electronics and components, continued advancements in intrinsically safe technologies and growing industry demand suggest a clear pathway forward. Overall, S.P.I.D.E.R. not only enhances safety and efficiency but also aligns with existing maintenance workflows and regulatory structures, making it a viable and impactful tool for the future of aircraft inspection and maintenance operations.

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Appendix

Detailed relevant ATEX Information

As it can be difficult to find ATEX rating rules for electronics, the United States equivalent was also referenced: the National Electrical Code (NEC) of Class I and Division I which defines it as follows: “Class I locations are those in which flammable vapors and gases may be present... Division 1: In which ignitable concentrations of hazards exist under normal operation conditions and/or where hazard is caused by frequent maintenance or repair work or frequent equipment failure” [14]. We will be referencing Jet A and Jet A-1 fuel which can be considered the same fuel for our design purposes even though Jet A is used more in the United States and Jet A-1 is used more internationally. The main differences between the two are their freezing points which are not relevant to our design [15]. We will not be considering applications to fuel tanks that house Jet B fuel due to its higher flammability, as it has a flash point of 0°F [16]. The Jet A and Jet A-1 fuels did not fall under group definitions from the NEC which included gasoline, acetylene, and other gases and vapors, as Jet A and Jet A-1 are less volatile and have a higher flash point than the listed groups. The closest classification found would be in Group A with acetylene; however, the jet fuel is less volatile. The ASTM states that the flash point for Jet A-1 fuel is 100.4°F [17]. The Federal Aviation Administration (FAA) stated that Jet A has an auto-ignition temperature of 435-450°F [18]. Since the auto-ignition temperature is between 419-446°F, Table F within “Class/Division Hazardous Location” from Rockwell Automation gives the temperature class for permissible surface temperature for our electrical equipment as T2D [14].

Regarding the environment inside the fuel tank, the FAA considers a recently drained fuel tank to be unheated, as in no active heat source is acting on the system. According to this definition, we can evaluate the environment in the fuel tank as follows, “The equilibrium temperature for a totally unheated tank will be very close to the air temperature...” [19]. The application of S.P.I.D.E.R. in this context should be limited to temperatures below 100°F. We expect this not to be a barrier, as S.P.I.D.E.R. is designed for checks that are performed in controlled hangars. The FAA describes comfort zones for working conditions for workers performing light work to be up to 80°F [20]. Though the FAA does not have a strict rule on the internal temperatures of hangars, all declarations of working environments indicate temperatures below 100°F which keeps the fuel tanks within a significantly safe range for S.P.I.D.E.R. to operate.

Camera/Field of View Calculations [21]

The camera to be chosen is an RGB camera with a resolution of 1920 x 1080p at 30 frames per second, with a diagonal field of view (DFOV) somewhere in the range of 80-85 degrees. With these specifications, the camera will be able to reliably pick up scratches or imperfections that are 2-3mm in length. This is determined by the number of pixels the camera covers in the vertical and horizontal dimensions. This is determined by using the following equations:

$$\text{Horizontal Width} = 2D \times \tan\left(\frac{\Theta_h}{2}\right)$$

Where:

- D = Distance of object
- Θ_h = Horizontal FOV angle

$$\text{Vertical Width} = 2D \times \tan\left(\frac{\Theta_v}{2}\right)$$

Where:

- D = distance of object (mm)
- Θ_v = vertical FOV angle (degrees)

$$\text{Horizontal Scale} = \frac{W_h}{N_h} = S_h$$

Where:

- N_h = number of horizontal pixels (pixels)
- W_h = horizontal scene width (mm)
- S_h = Horizontal Scale (mm/pixel)

$$\text{Vertical Scale} = \frac{W_v}{N_v} = S_v$$

Where:

- N_v = number of vertical pixels (pixels)
- W_v = vertical scene width (mm)
- S_v = Vertical Scale (mm/pixel)

$$L_{min,v} = P_{min,v} \times S_v, \quad L_{min,h} = P_{min,h} \times S_h$$

Where:

- P_{min} = Number of pixels wanted to be laid across the defect (10 pixels for reliability)
- S = scene width (mm)
- L_{min} = minimum length of detectable feature

Servo Motor Torque Calculations

$$\tau = \frac{F \times r}{\# \text{ of Legs}}$$

Where:

- τ = torque required (kg – cm)
- F = Estimated Weight: 5.03 kg or 11.1 lbs
- r = Femur Length: 15.24 cm

$$\text{Required Torque for a 2-Legged Lift} = \frac{5.03 \text{ kg} \times 15.24 \text{ cm}}{2 \text{ legs}} = 38.33 \text{ kg – cm}$$

Battery Calculations

Component:	Usage (W)	Units	Operating time (Hours)
22 Servos	67.2	W	2
Nvidia Jetson	10	W	2
Camera	2.2	W	2
NDI Low Penetration	10	W	1
Total	168.8	Whr	-
Battery Capacity (12 V System)	14.0	Ah	-