S.P.I.D.E.R.

Surveying Platform and Inspection Device for Enclosed Regions

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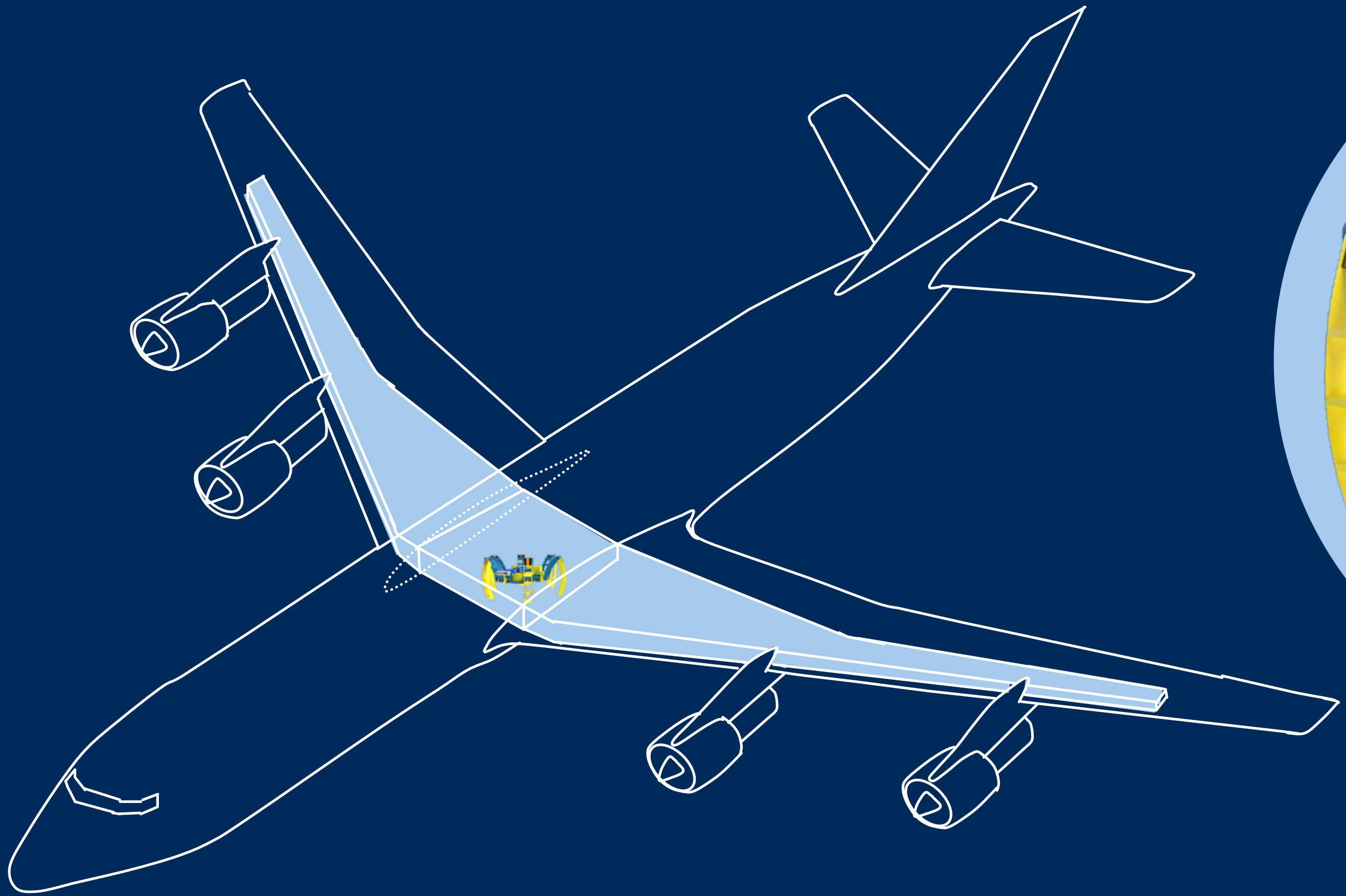

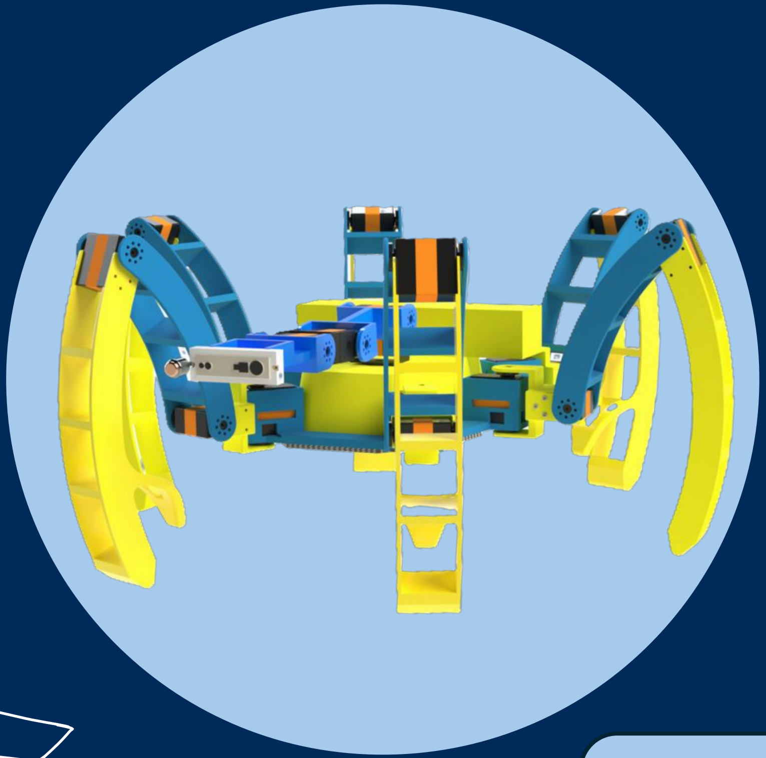

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INITIAL RESEARCH

Researching current development

Inspection device

Understanding industry needs

[1,2]

MOTIVATION

After interviewing 20 aircraft maintenance technicians, a common theme emerged: **fuel tank inspections** on commercial aircraft are **problematic:**

- Tight Workspace
- Hot Environment
- Time Consuming
- Odor Sticking for Days
- Skin Irritation
- Health Risks

- In-depth fuel tank inspections required: **6-10 years** [3,4,5]
- Air purge: **6-24 hours** [3]
- Human inspection time: **8 man-hours** [3]
- Airlines lose **$100,000** per day for each grounded airplane

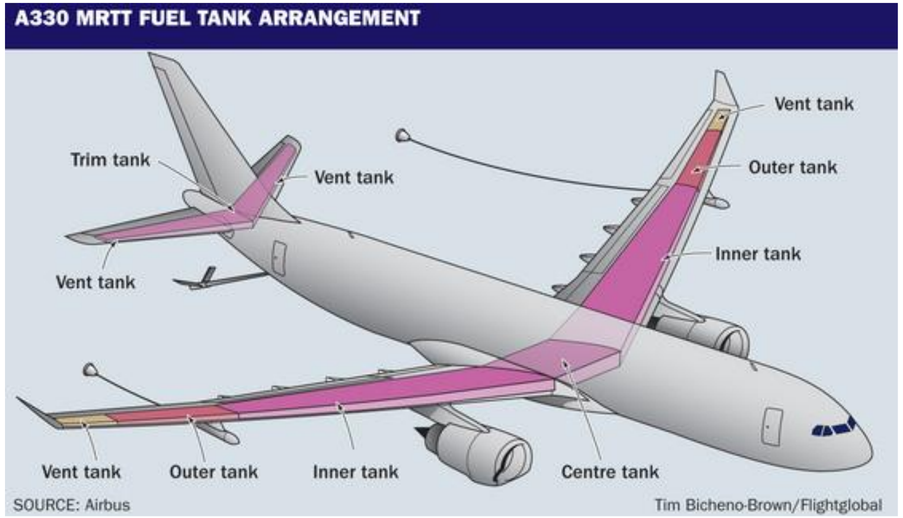
CURRENT INSPECTION PROCESS

[2,6,7,8]

INSPECTION REQUIREMENTS

Airworthiness directive (AD): FAA legally binding required maintenance to keep aircraft 'airworthy' (EASA in Europe) target issues such as cracking, corrosion, or wear

- Airbus A380 – Wing Rib Feet Cracking
  - Requires detailed **visual inspection** and **eddy current** or **ultrasonic** if needed, requires **entry into fuel tank**
- Boeing 777 -- Center Fuel Tank Web Inspections
  - Requires **tank entry** for **visual inspection** of the **forward and aft webs for cracks**, follow up repairs require **eddy current**
- Boeing 767 – Center Wing Tank Pumps Wiring and Structure
  - Requires **tank dive** and **visual inspections** of **pumps/wiring/structure** around this area
- Boeing 737 Next Gen (737-600/-700/-800/-900) & 737 MAX
  - Requires **visual inspection** inside tank of the **forward and aft fuel tank web** along with surface high-frequency **eddy current**



[9,10]

OVERVIEW

S.P.I.D.E.R. is a hexapod robot that is designed to carry out aircraft **fuel tank inspections**

Six legs provide **stability** and **maneuverability**

An **eddy current** probe attached to the end of the arm will provide NDI to detect subsurface defects

Equipped with a movable **camera** arm that provides 360º view for **visual inspection** to detect **cracks, corrosion, and wire chafing**

S.P.I.D.E.R. will be fully **ATEX Zone 0 rated**, meaning it is safe to enter the fuel tank when fuel vapors are present

ATEX ZONE 0 / NEC CLASS 1

ATEX: **At**mosphères **Ex**plosibles (EU)
NEC: **N**ational **E**lectric **C**ode (US)

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 [11]

All material, electrical, and mechanical design choices must prevent ignition under worst-case conditions

ATEX ZONE 0 / NEC CLASS 1

Protection:

- Independent 2nd Failsafe
- 2 Independent Faults at the Same Time [12, 13]

Recommended Operating Equipment Temperature:

<100.4 ˚F

Flash point of Jet A-1 [14]

MATERIAL [PRIMARY]

- PEEK 30% Carbon Fiber:
  - Density: 1.4 g/cm^3 [15]
  - Encasement of motors and electronics
  - Already used in aerospace, automotive, medical, and electronics industries [16]

- Benefits of Carbon Fiber [20]
  - Strength and Stiffness
  - Thermal conductivity
  - Wear resistance
  - Creep resistance

	Required / Recommended	PEEK 30% Carbon Fiber
Surface Resistivity [15, 17]	$<10^9$ Ω/sq	$<10^5$ Ω/sq
Flammability Rating [15]	V-0	V-0
Triboelectric Breakdown [18]	< 3 MV/m	69 V/m
Max Cont. Operating Temperature [15, 19]	>221 ˚F	480 ˚F

The max exposed surface temperature of all components in the fuel tank must be less by a safe margin than the lowest expected autoignition temperature of the fuel vapor (Jet A-1: 435˚F) [21]

MATERIAL [PRIMARY]

Triboelectric Breakdown Calculation

Assumptions:

- PEEK 30% CF σ value can be approximated as PTFE's value
- Charge leakage and humidity effects lower triboelectric charge density [23, 24, 25]

$$E = \frac{\sigma}{\varepsilon_0}$$

Electric Field

$$E = \frac{V}{d}$$

Charge

$$Q = \sigma A$$

Parallel-plate approx.

$$V = \frac{\sigma d}{\varepsilon_0}$$

Al to PEEK

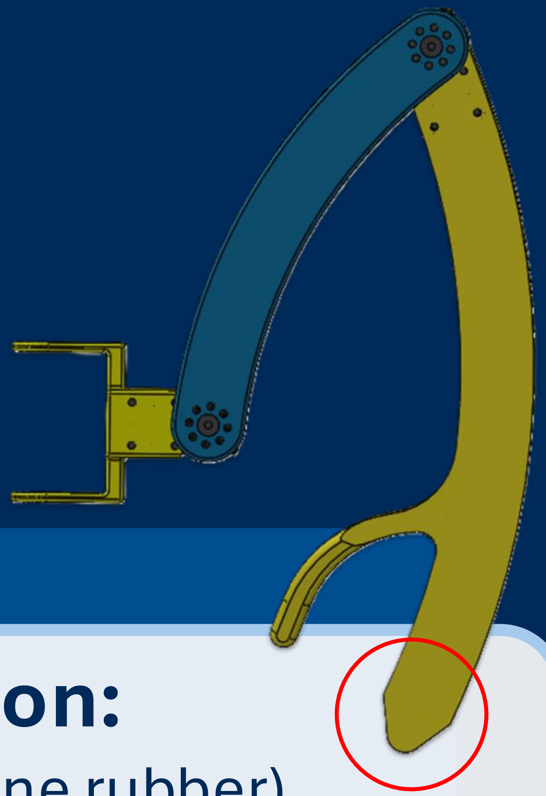
E = 69 V/m = 69 V/m

< 3 MV/m (breakdown of air)

$$\sigma(\textit{triboelectric charge density}) = -6.1\ x\ 10^{-9}\,\frac{\mathrm{C}}{m^2}$$ [22]

$$\varepsilon_0(\textit{permittivity of free space}) \approx 8.854\ x\ 10^{-12}\ F/m$$

MATERIAL [FEET]



Requirements:

- Oil-resistant [26]
- Static-dissipative
  - Prevents charge buildup
  - Prevents spark ignition
  - Prevents full conductivity
- Grippy material

Recommendation:

- NBR (nitrile butadiene rubber)
- Commonly used in chemical applications [27]
- Typical Properties
  - Surface Resistivity: 10^3-10^8 Ω /sq [28]
  - Max Temperature: ~200 ˚F [26]

INSPECTION DEVICES

Camera:

- Visual Inspection: Camera attached to 360˚ arm
- Must be tested ATEX Zone 0 Rated
  - Spark, Temperature, Sealed Enclosure, Battery Safety
- Resolution of 1920 x 1080p at 30 frames per second
- Needs a DFOV in the range of 80˚- 85˚

Light:

- Light source to illuminate the fuel tank
- ATEX Zone 0 Rated – Does Exist

Camera Calculations

$$Horizontal\ Scene\ Width = 2D \times \tan(\frac{\theta_h}{2})$$

Where:
D = Distance of object
Θ_h = Horizontal FOV angle

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

Where:
N_h = number of horizontal pixels (pixels)
W_h = horizontal scene width (mm)

$$Vertical\ Scene\ Width = 2D \times \tan(\frac{\theta_v}{2})$$

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

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

Where:
N_v = number of vertical pixels (pixels)
W_v = vertical scene width (mm)

- $L_{min} = P_{min} \times S$

Where:
P_{min} = number of vertical pixels (pixels)
S = vertical scene width (mm)
L_{min} = minimum length of detectable feature

INSPECTION DEVICES

Non-Destructive Testing (Eddy-Current):

- Eddy current inspection is widely used in the aircraft industry to detect subsurface structural defects.
- During initial implementation, an AMT will review the probe data to identify defects.
- Eddy current is already used in aircraft fuel tanks, but not during the air-purging process.
- There are currently no ATEX Zone 0-rated eddy-current probes available.
    - Certify an off-the-shelf eddy current probe for ATEX Zone 0 use on the robotic system.

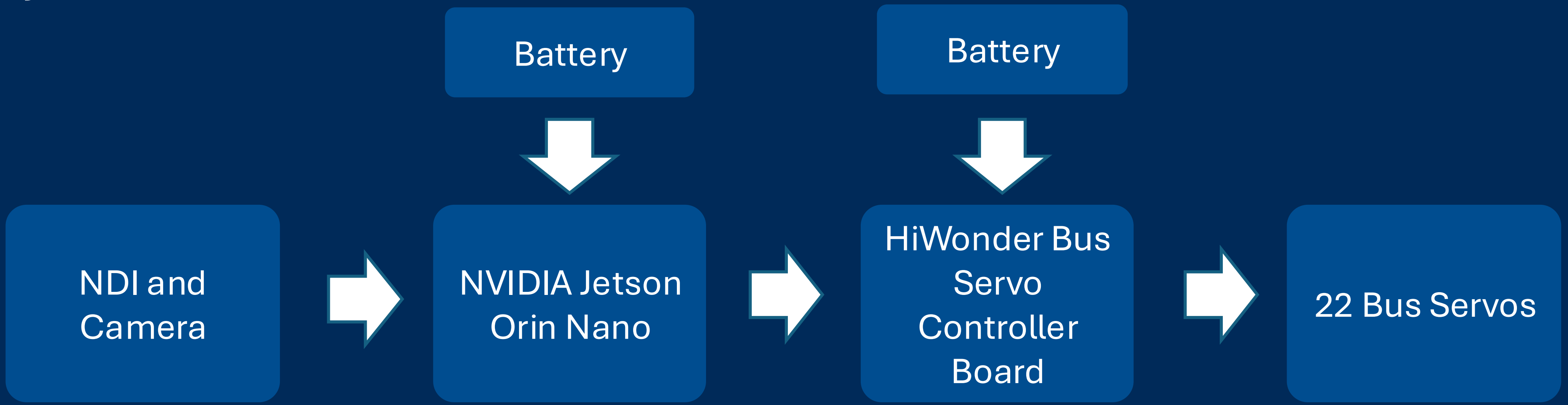
[29]

ELECTRICAL

Components:

- Motor controller: HiWonder Bus Servo Controller Board
- Servos: HiWonder Bus Servos
- NVIDIA Jetson Orin Nano 8GB
- Camera
- NDI probe
- Battery

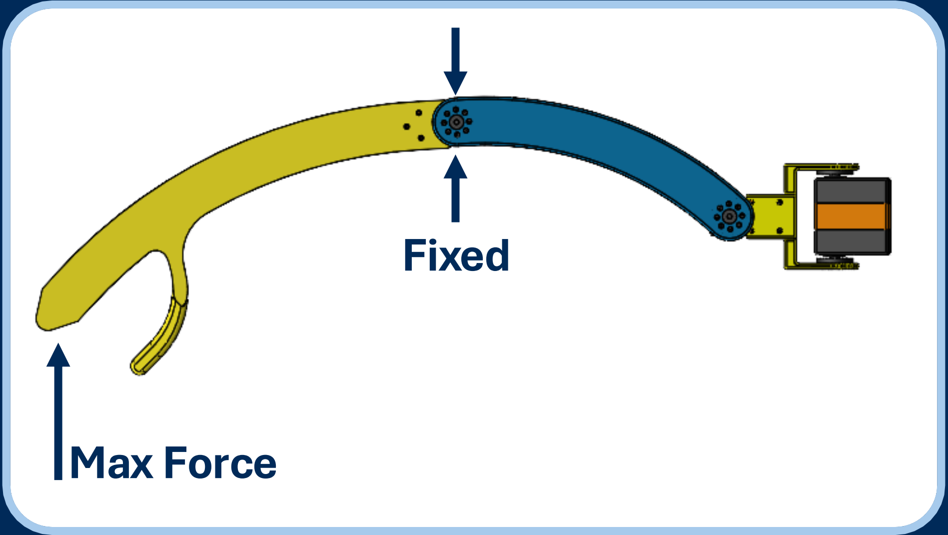
Component:	Usage (W)	Units	Operating time (Hours)
22 Servos	67.2	W	2
Nvidia Jetson	10	W	2
Camera	2.2	W	2
NDI Low Penetration	10	W	1
Total	168.8	W·hr	-
Battery Capacity (12 V System)	14.1	Amp·hr	-



MECHANICAL

$$\tau = \frac{F \cdot r}{\#\ of\ Grounded\ Legs}$$

Torque Calculations	
Total Weight	7.5 kg
Total Length of Leg Assembly	17.2 cm
Torque Required for 2 Leg Lift	64.5 kg · cm
Max Motor Torque (FOS = 2)	**129 kg · cm**



INVERSE KINEMATICS

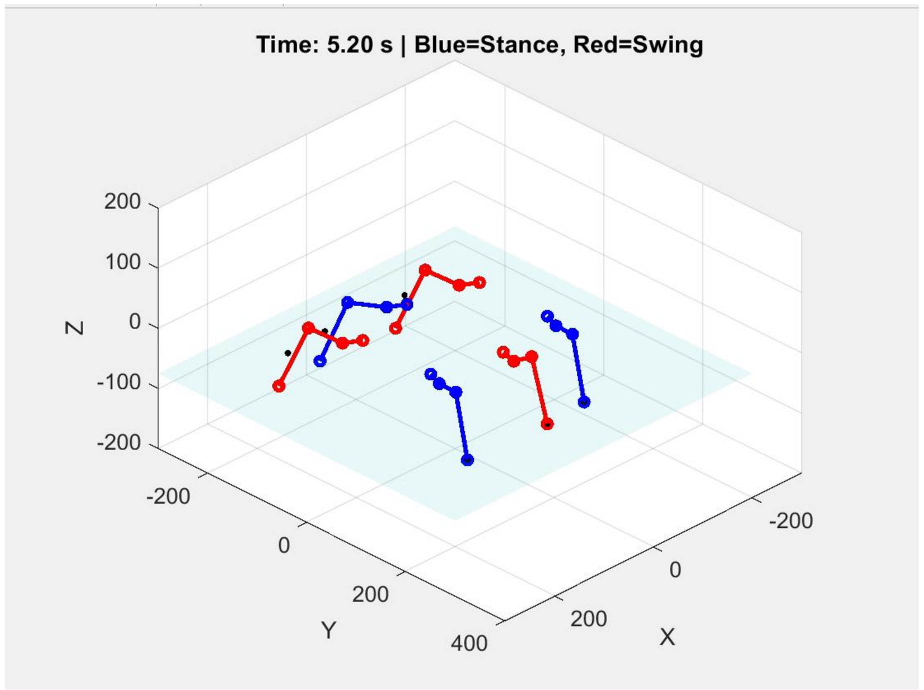
Calculates the angles for each of the 18 servos

A cartesian coordinate plane was established based on the orientation of each leg

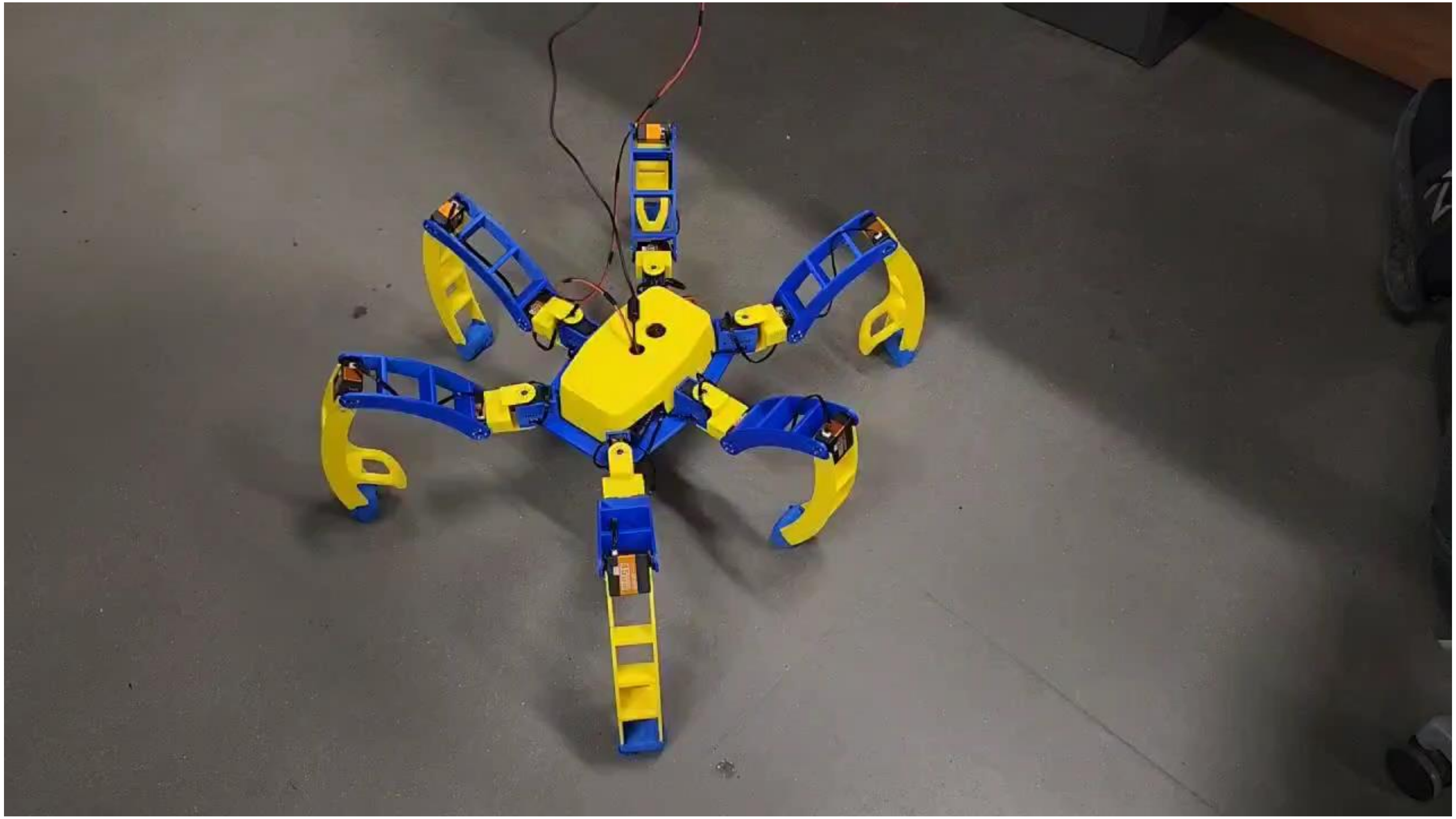
Core calculations solve for the angle of each servo based on the desired point for the leg to reach

Based on those core calculations, a desired path for the foot to create the step was generated

Once a step was generated, a walking gait was created by timing 3 legs to step while the other 3 are on the ground



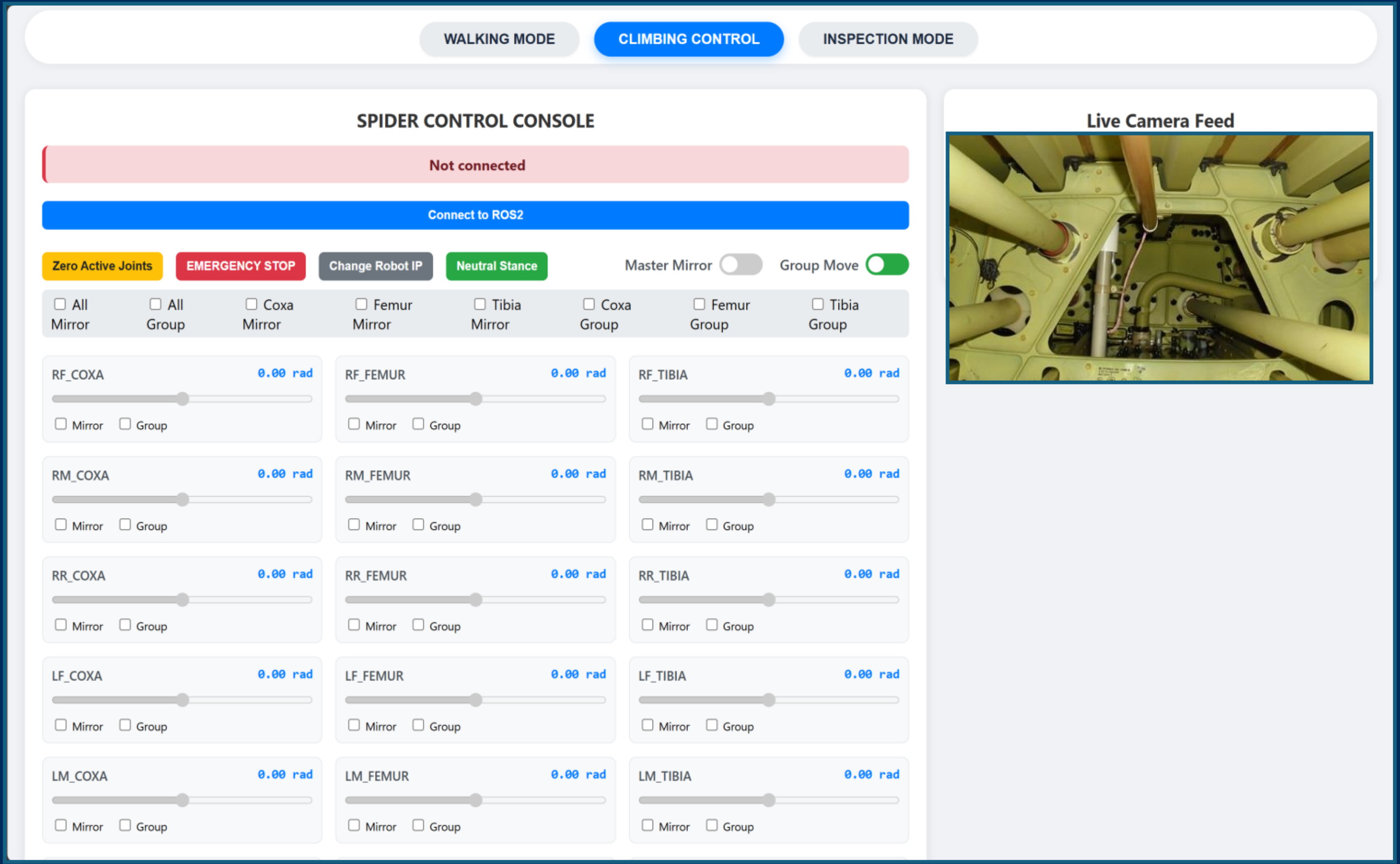
WALKING GAIT



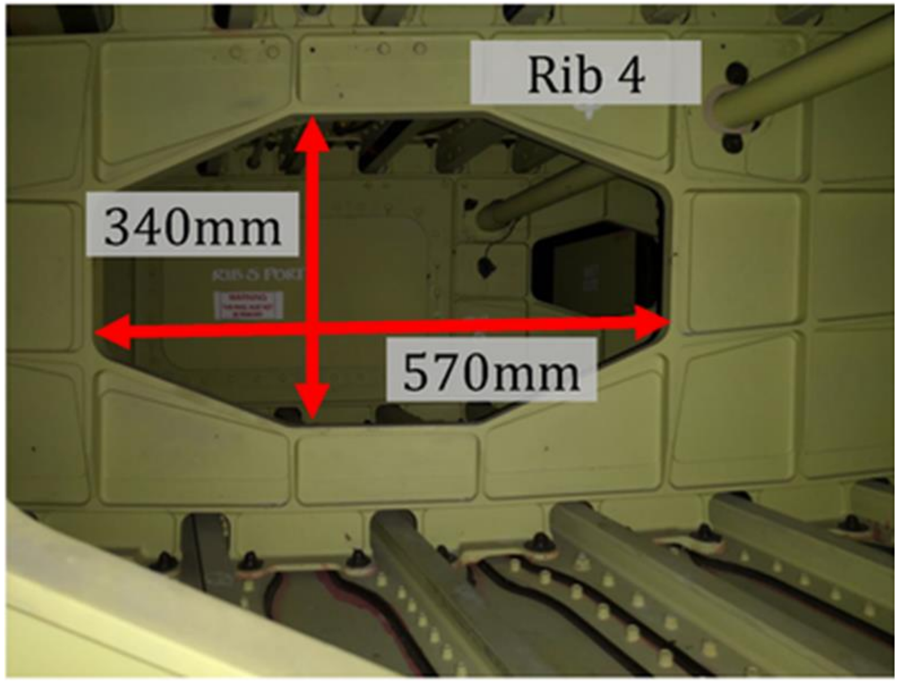
WEB-BASED GUI

Main features:

- Zero active joints
- Emergency stop
- Walking mode
- Inspection mode
    - Live camera feed
- Climbing Control
- Wireless connection



CLIMBING



[3]

Height to Gap: 11 in

Dimensions: 21.5 in x 13 in

IMPLEMENTING ISACC SIM/LAB

CREATE VIRTUAL ENVIRONMENT WITH NVIDIA OMNIVERSE
- Collaborate with airlines to model fuel tank geometry
- Add internal structures, obstacles, materials, and operating conditions

DEFINE REINFORCEMENT LEARNING OBJECTIVE
- Robot is rewarded for successfully making it through the hole
- Robot base is rewarded for not touching ground during traversal

TRAIN HEXAPOD IN SIMULATION USING REINFORCEMENT LEARNING (RL)
- Define state space, action space, and reward function
- Train in Isaac Lab (RL framework)
- Optimize for climbing, stability, and traversal success

IMPLEMENT CODE WITH NVIDIA + ROS ARCHITECTURE
- Export trained policy/model
- Integrate with ROS (control, perception, logging)
- Deploy on NVIDIA Jetson platform

TEST IN REAL ENVIRONMENT
- Deploy on a physical robot
- Test in a controlled environment and fuel tank mock-up
- Evaluate performance, safety, and robustness

EVALUATE & ITERATE
- Compare simulation vs. real-world performance
- Identify gaps and failure cases
- Refine environment, reward, or model
- Retrain and redeploy as needed

ITERATE

Refine, retrain, and improve

END RESULTS
- Robust, RL-enabled hexapod ready for fuel tank inspection

FUTURE SAFETY IMPLEMENTATION

Inherent protection code

Servo health monitor (stall current and temperature)

Low battery triggers auto return home

Temperature sensor for inside S.P.I.D.E.R. triggers active cooling systems

Oxygen / gas sensors for live status of tank:
Before human entry:
- 21% oxygen
- Gas concentration <10% of lower explosion limit [3]

ECONOMICS

Airlines lose **$100,000** per day for each grounded airplane

For a fleet of 800: **$8,000,000** lost per year

Conceptual: The goal of S.P.I.D.E.R. is to sell the service of fuel tank inspections, which is a commonly contracted service by airlines.

- With S.P.I.D.E.R., airlines can save **$2,000,000 per year**
- Cost of first prototype: **$1,000**
- Estimated cost of components of conceptual: **$10,000**

TIMELINE TO IMPLEMENTATION

2026

Preliminary Design and Initial Prototyping

- Develop initial mechanical, electrical, and software prototypes
- Begin laboratory mobility and sensing validation
- Integrate full hexapod platform with imaging, NDI sensing and onboard computing
- Conduct controlled confined-space mobility testing and inspection accuracy studies

2028

Relevant Environment Testing

- Testing in representative fuel-tank mockups and metallic confined spaces
- Validate communication reliability and operator workflows
- Refine electrostatic-safe materials
- Engage with certification and regulatory stakeholders

2030

Pre-Certification and Operational Demos

- Mature safe power, sensing, and actuation subsystems
- Extended duration inspection trials and reliability testing
- Demonstrate integration with maintenance documentation and NDI processes
- Prepare safety case documentation and certification test plans

2032

Certification Testing and Field Evaluation

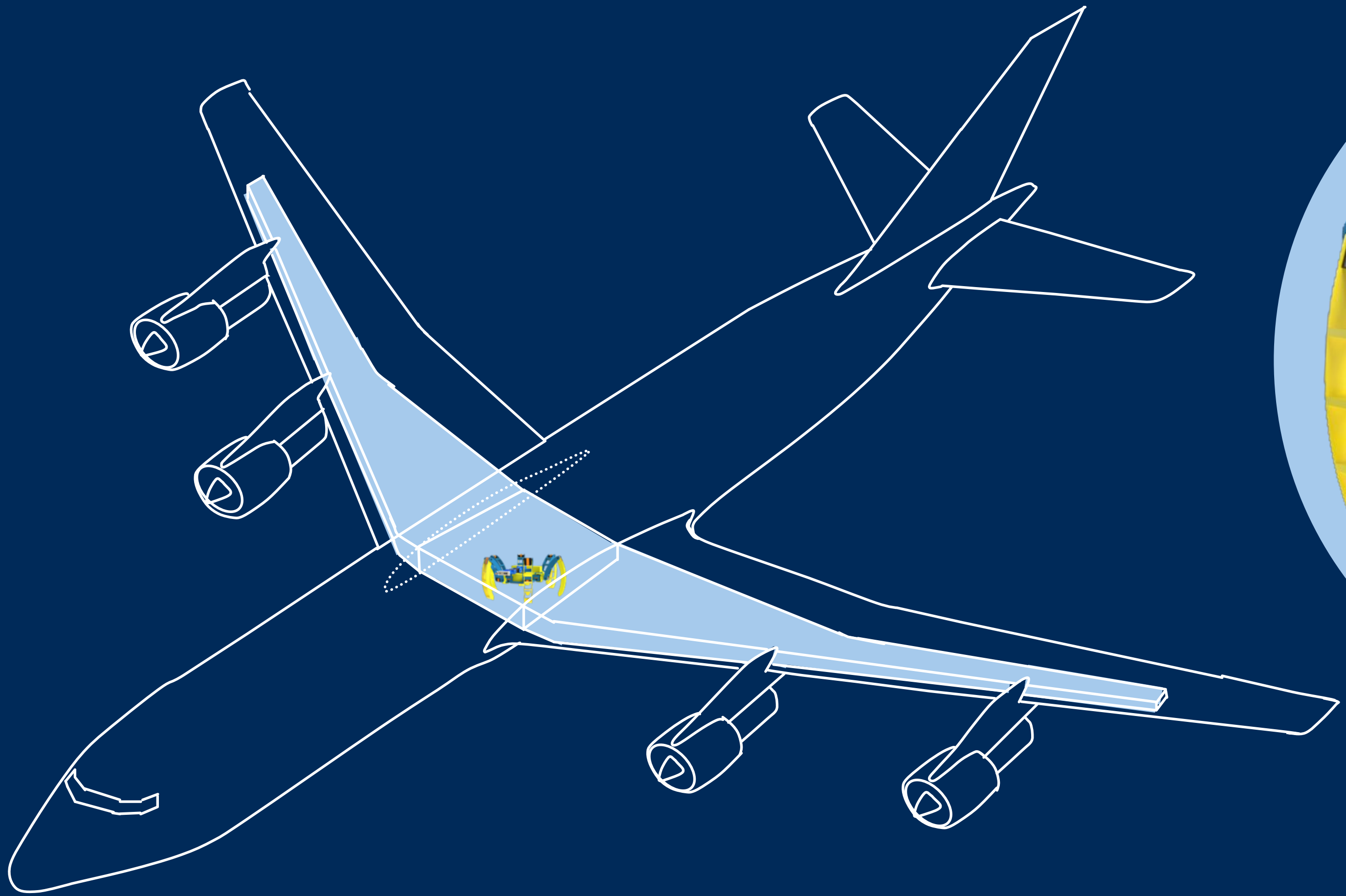
- Formal Hazardous-environment testing
- Supervised demos in operational environments
- Validate reduction in human tank entry time, inspection duration, and downtime

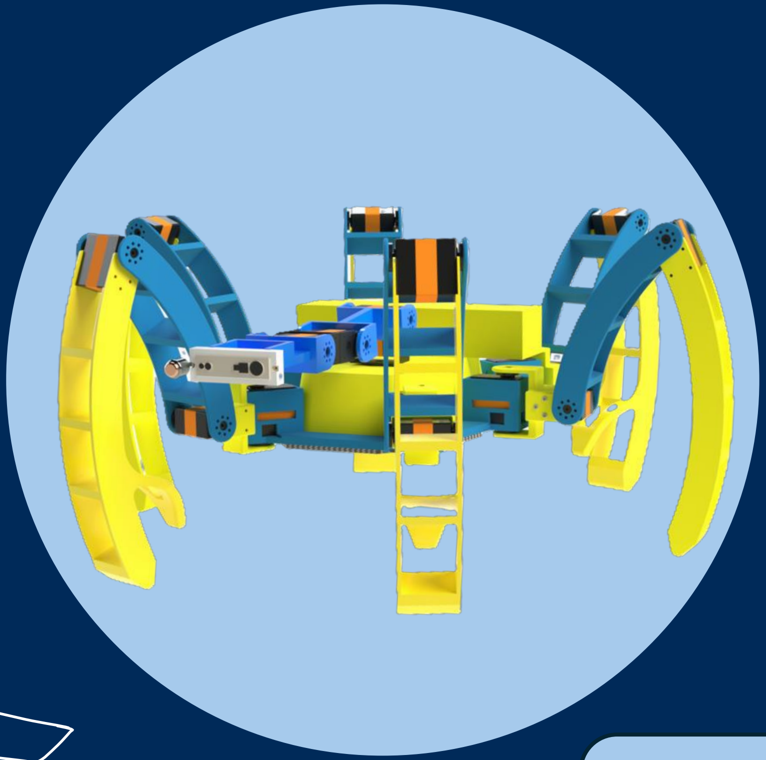
2035

Initial Operational Implementation

- Achieve operational approval for restricted commercial use
- Deploy early production systems within partner maintenance organizations
- Collect operational data to support broader adoption
- Transition to sustained manufacturing, training, and lifecycle support

Thank You
Questions?





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OTHER

$$Capacitance$$

$$C = \frac{\varepsilon_0 A}{d}$$

”Equipment that does not exceed a maximum surface temperature of 212°F(104°F ambient temperature) is not required to be marked with a temperature code (NEC).” [*]