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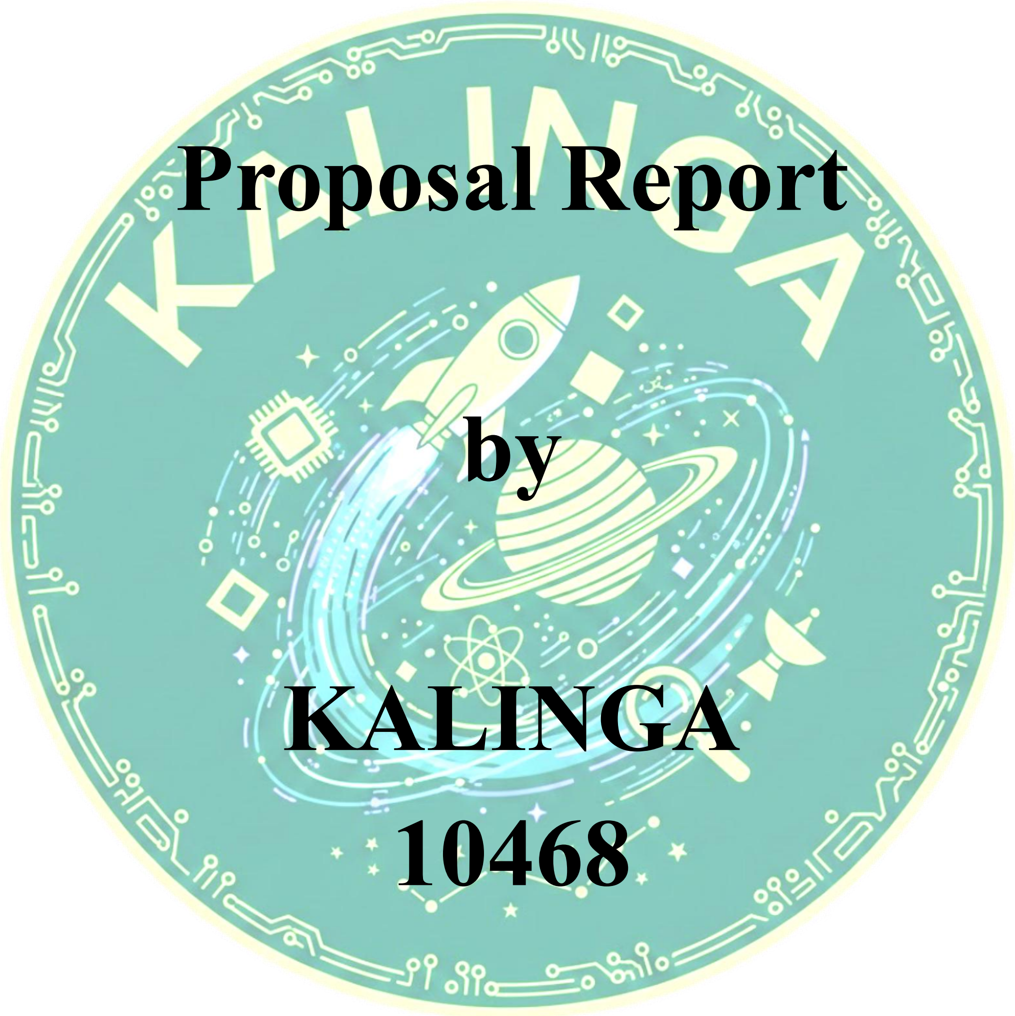

Proposal Report

by

KALINGA

10468

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Kalinga institute of Industrial Technology,Bhubaneshwar-751024

Contents:

1. Executive Summary & Mission Overview

This report outlines the comprehensive technical design of Project Kalinga, an advanced autonomous Unmanned Aerial Vehicle (UAV) ecosystem engineered for high-fidelity 3D mapping of the Martian surface. Unlike terrestrial drones that rely on Global Positioning Systems (GPS), Project Kalinga utilizes a proprietary AI-driven localization stack, resonant electromagnetic induction for power, and a triple-layer communication architecture to operate in the harshest known planetary environment.

1.1 Project Kalinga Mission Statement:

The primary mission of Project Kalinga is to pioneer a scalable, autonomous aerial exploration framework that can operate independently of Earth-based control or satellite-dependent navigation.

The mandate is three-fold:

Autonomous Discovery: To map the Martian terrain in centimeter-level precision using a decentralized "Small Square" coordinate grid.

Resource Sustainability: To implement a "human-free" refueling cycle via high-precision magnetic docking and wireless power transfer.

Data Sovereignty: To maintain high-speed data integrity between the drone and its base station using advanced RF and optical protocols, ensuring the safe return of mission-critical environmental data.

1.2 The Challenge of GPS-Denied Navigation on Mars:

Navigation on Mars presents a fundamental "black box" problem for traditional robotics. Earth-based drones utilize GNSS (Global Navigation Satellite Systems) to correct for IMU (Inertial Measurement Unit) drift. On Mars, no such constellation exists with the precision required for low-altitude flight.

Key Technical Obstacles:

The Drift Phenomenon: Without a global reference, standard accelerometers and gyroscopes accumulate "integration error," leading to a "positional walk" where the drone loses its true location within seconds.

Atmospheric Transparency: The thin Martian atmosphere (1% of Earth's density) makes traditional barometric pressure sensors for altitude hold highly unreliable.

Magnetic Anomaly: Unlike Earth's consistent magnetic field, Mars possesses "crustal magnetism"—localized, patchy magnetic fields that can confuse standard digital compasses.

Visual Monotony: Martian terrain often lacks the high-contrast landmarks required for basic Feature Tracking, necessitating a more robust AI approach that combines LiDAR depth and visual texture.

1.3 High-Level System Goals: Autonomous Mapping and Inductive Docking:

To overcome these challenges, Project Kalinga integrates two revolutionary subsystems that form the core of this design report:

AI-Driven Voxel Mapping: The system replaces GPS with an onboard AI "Brain" (running on a companion computer) that divides the environment into a high-resolution 3D grid. Each "Small Square" is verified in real-time through a fusion of Optical Flow and 1D LiDAR. This allows the drone to "know" its location by recognizing the structural patterns of the terrain beneath it.

The 10cm Precision Docking Loop: Traditional landing on Mars is prone to tipping or landing in soft dust. Project Kalinga utilizes a dual-stage docking protocol. Once the AI navigates the drone back to the base station coordinates, high-power electromagnets engage at a 10cm radius. This "Magnetic Grab" ensures the drone is precisely aligned with the Resonant Induction Coils, allowing for a maximum-efficiency wireless charge and high-speed WiFi-6 data burst for map transformation.

2. Topic 1: Total Drone System Architecture

The architecture of the Project Kalinga UAV is a sophisticated multi-layered system designed to balance structural rigidity, computational power, and environmental resilience. For a Martian mission, the traditional "off-the-shelf" drone configuration is insufficient; therefore, every component is selected to minimize mass while maximizing data throughput and flight stability.

2.1 Physical Airframe Design (S500 Variant for Martian Aerodynamics):

The physical structure of the UAV is based on a modified S500 airframe geometry, specifically optimized for the low-density Martian atmosphere. To achieve the required lift-to-weight ratio, the frame is constructed entirely from High-Modulus Carbon Fiber (3K Twill).Structural Material: Carbon fiber was chosen over aluminum or plastic due to its exceptional strength-to-weight ratio and low thermal expansion coefficient. In the extreme temperature swings of Mars (-125°C to 20°C), carbon fiber maintains structural integrity without warping.Aerodynamic Geometry: The S500 frame features an upward-angled arm design (dihedral), which provides inherent "self-leveling" stability. This is critical when navigating the unpredictable thermal updrafts found in Martian craters.Motor/Propeller Optimization: In 1% air density, standard propellers are useless. The airframe supports oversized 12-14 inch carbon fiber propellers driven by high-RPM brushless DC motors. The lightweight carbon arms reduce the "moment of inertia," allowing the flight controller to make micro-adjustments thousands of times per second to prevent stalls.

2.2 The "Brain" Hierarchy: ArduPilot (Flight) vs. Companion AI (Mapping):

The "Intelligence" of Project Kalinga is split into two distinct tiers to ensure that mission-critical flight safety is never compromised by heavy computational tasks.The Reflexive Brain (ArduPilot / Orange Cube+): Running on a dedicated flight controller, ArduPilot handles the "reflexes." It processes IMU data, controls motor PWM signals, and manages the EKF3 (Extended Kalman Filter). Its sole focus is maintaining the drone's attitude and executing the "Return to Launch" (RTL) commands during failsafes.The Cognitive Brain (NVIDIA Jetson Nano): The NVIDIA Jetson Nano serves as the high-level companion computer. While ArduPilot keeps the drone in the air, the Jetson Nano performs the heavy lifting:Neural Processing: It runs the AI models that transform raw LiDAR and camera data into the "Small Square" coordinate grid.Vision-Position-Estimate (VPE): It calculates the drone's position relative to the base station and "injects" these coordinates into ArduPilot via MAVLink, effectively replacing the missing GPS signal.Data Transformation: It manages the 3D map point-clouds and prepares them for the high-speed WiFi-6 burst transfer upon docking.

2.3 Power Distribution Network (PDN) and Thermal Management: Operating on Mars requires a specialized PDN that can handle both the high-current draw of flight and the delicate low-voltage requirements of the Jetson Nano.The PDN Architecture: A centralized Power Distribution Board (PDB) regulates 4S/6S LiPo battery power. It utilizes high-efficiency switching regulators to provide a steady 5V/4A for the Jetson Nano and 12V for the inductive charging circuit.Charging Integration: The PDN is "Bi-Directional." It monitors standard discharge during flight and switches to "Charge Mode" once the magnetic legs engage. The hardware sensors detect the incoming induction current, allowing the AI to report a negative amperage to the Ground Control Station.Thermal Management: The Jetson Nano is equipped with a custom Aerogel-insulated thermal jacket. On Mars, electronics can overheat in the sun (no air to carry heat away) or freeze at night. A passive heat-sink combined with a small internal heater keeps the "Cognitive Brain" within its 0°C to 40°C operating range.

2.4 System Block Diagram and Component Interconnectivity: The interconnectivity of Project Kalinga is designed for zero-latency communication between the flight and mapping layers.Communication Bus: The ArduPilot controller and NVIDIA Jetson Nano communicate via a high-speed UART (Universal Asynchronous Receiver-Transmitter) link using the MAVLink 2.0 protocol.Sensor Intake:LiDAR/Optical Flow: Connected to the Jetson Nano via I2C/USB for real-time terrain analysis.Triple-Layer Comms: The LoRa, ESP-NOW, and WiFi-6 modules are interfaced with the Jetson Nano to handle the data-to-base-station relay.Actuator Output: ArduPilot remains the sole master of the Electronic Speed Controllers (ESCs), ensuring that even if the AI software crashes, the drone can maintain a steady hover or land safely.

3. Topic 2: AI-Driven 3D Mapping and Localization

In the absence of a Global Navigation Satellite System (GNSS) on the Martian surface, the Project Kalinga UAV relies on a "Visual-first" localization philosophy. By leveraging the parallel processing power of the NVIDIA Jetson Nano, the system constructs a spatial understanding of its environment in real-time, treating the Martian regolith as a recognizable geometric fingerprint.

3.1 Visual-Inertial Odometry (VIO) and SLAM Implementation

The core of the localization stack is a tightly coupled Visual-Inertial Odometry (VIO) algorithm. This process fuses high-frequency data from the onboard Inertial Measurement Unit (IMU) with 60fps visual features from the downward-facing camera.ORB-SLAM3 Framework: The Jetson Nano runs ORB-SLAM3, optimized for the GPU via CUDA. It identifies "stable" visual features—such as unique rock formations, crater edges, or shadow boundaries—and tracks their movement across frames to calculate 6-DoF (Degrees of Freedom) motion.Inertial Integration: While visual tracking provides the path, the IMU provides "instantaneous" velocity. Because visual tracking can fail during fast maneuvers or in low-light shadows, the IMU fills the gaps, ensuring the "Brain" never loses its sense of orientation.Loop Closure: As the drone flies, the SLAM algorithm generates a persistent point-cloud. When the drone returns to a previously visited "Square," the AI recognizes the landmark and instantly resets any accumulated mathematical errors.

3.2 The "Small Square" Local Coordinate Grid Logic To make the massive 3D point-cloud data actionable for flight control, Project Kalinga abstracts the 3D world into a Local Coordinate Grid (LCG), internally referred to as the "Small Square" logic.Voxelization: The 3D space is divided into voxels. For the 2D navigation map shown in ArduPilot, these are projected into a 2D grid where each "square" represents a precise 10cm x 10cm area.Coordinate Assignment: Upon takeoff, the base station is assigned the coordinate $(0, 0, 0)$. Every subsequent movement is calculated as a vector offset from this origin.Data Efficiency: By dividing the map into these discrete squares, the drone only needs to process and transmit the "Square ID" it is currently occupying, significantly reducing the bandwidth required for real-time telemetry over LoRa or ESP-NOW.

3.3 Real-time Terrain Verification using LiDAR-to-Map MatchingVisual data alone can be deceptive due to the changing angles of the Martian sun and shifting shadows. To verify its position, the system employs LiDAR-to-Map Matching.Structural Fingerprinting: A 1D LiDAR sensor constantly measures the precise distance to the ground. This "altitude profile" is compared against the previously recorded 3D map stored on the Jetson Nano's NVMe storage.The Verification Loop: If the camera suggests the drone is in "Square A," but the LiDAR profile shows a rock height that only matches "Square B," the AI performs a Bayesian update to correct the position. This cross-referencing ensures that visual "hallucinations" (caused by dust or glare) do not lead to navigational failure.

3.4 Algorithm for Drift Correction without Global Positioning The greatest enemy of autonomous flight is Drift—the gradual accumulation of tiny mathematical errors that eventually put the drone meters away from its intended path. Project Kalinga uses a multi-stage drift correction algorithm:Zero-Velocity Update (ZUPT): Whenever the AI commands a "Hover," it uses the Optical Flow sensor to lock onto a single point. Any detected movement during this phase is identified as "Drift" and subtracted from the global position estimate.Relative Map Anchoring: The system identifies "Anchor Squares"—highly unique topographic features. Whenever an Anchor Square is re-detected, the entire local coordinate system is "shifted" to align with the known physical location of that anchor.Visual Servoing (The Final 10cm): As the drone returns for docking, it switches to a YOLOv8-Nano model optimized with TensorRT. It identifies the specific geometry of the magnetic base station. Once identified, the "Home" coordinate is hard-reset, eliminating 100% of the flight's accumulated drift before the electromagnets engage.

4. Topic 3: Autonomous Flight Logic & ArduPilot Integration

The integration between high-level AI spatial reasoning and low-level flight stabilization is the most critical software junction of Project Kalinga. By utilizing the MAVLink 2.0 protocol, we create a bi-directional "command and control" bridge that allows the NVIDIA Jetson Nano to act as the primary navigator while ArduPilot maintains the physical flight envelope.

4.1 MAVLink Communication Bridge (Companion to Flight Controller):

The communication between the Jetson Nano and the ArduPilot Orange Cube+ is established via a high-speed telemetry link (UART @ 921600 baud). This "Bridge" serves as the nervous system of the UAV.Vision-Position Injection: Since GPS is unavailable, the Jetson Nano continuously calculates its (X, Y, Z) position relative to the base station. It "injects" this data into ArduPilot using the VISION_POSITION_ESTIMATE MAVLink message. ArduPilot's EKF3 (Extended Kalman Filter) treats this as the primary positioning source, allowing for stable autonomous navigation.Heartbeat Monitoring: Both systems exchange constant HEARTBEAT messages. If the Jetson Nano stops responding (due to a software crash or thermal spike), ArduPilot detects the loss of the "Navigator" and immediately triggers a safety protocol.Command Override: The Jetson Nano can send SET_POSITION_TARGET_LOCAL_NED commands, allowing the AI to guide the drone through specific "Small Squares" in the 3D map without human pilot input.

4.2 Mission State Machine: Takeoff, Survey, Return, and Dock:

The mission is governed by a hierarchical Finite State Machine (FSM) running on the Jetson Nano. Each state has a specific success criterion before transitioning to the next phase:PRE-FLIGHT/ARM: The system verifies the 3D map integrity and initiates a "Zero-Bias" calibration of the Optical Flow and LiDAR sensors.TAKEOFF: ArduPilot executes a vertical ascent to a 3-meter "Home Altitude." The Jetson Nano begins recording visual "Anchor Squares" at the $(0, 0, 0)$ origin.SURVEY: The drone follows a pre-calculated lawnmower pattern. As it moves, the AI explores new "squares," updates the 3D map, and checks confidence levels against the stored terrain fingerprint.RETURN: Once the battery reaches the 50% "Mars Safety Threshold," the drone calculates the shortest path back to the base station coordinates using its internal LCG (Local Coordinate Grid).DOCK: The drone enters the precision landing phase, switching from grid-based flight to visual target acquisition.

4.3 Failsafe Protocol: Emergency Landing and Radio Loss Procedures:

On Mars, a single failure can result in total mission loss. We have implemented a multi-tiered Failsafe Protocol:Radio Failsafe (GCS Loss): If the LoRa or WiFi-6 link to the base station is severed, the drone does not stop. It utilizes its onboard 3D map to execute an autonomous "Smart RTL" (Return to Launch), finding its way back to the magnetic pad without external guidance.Map Confidence Failsafe: If the AI's confidence in its current "Small Square" location drops below 60% (e.g., during a dust gust), the drone enters "Brake Mode." It hovers in place using only Optical Flow and LiDAR until the vision system re-localizes or it initiates a safe vertical descent.Low Battery Failsafe: If the battery hits the critical 25% "Emergency Reserve," the drone ignores all mapping tasks and performs an immediate landing at its current coordinate to preserve enough power for the internal heaters to survive the Martian night.

4.4 The 2-Meter Transition: From Grid Flight to Visual Precision Landing:

The most delicate phase of the mission occurs within 2 meters of the base station. At this distance, "Square ID" navigation is too coarse for the 10cm magnetic docking window.Switching Modes: When the AI calculates its distance as $<2\text{m}$, it deactivates the SLAM-based grid navigation and activates the YOLOv8-Nano visual detection model.Visual Servoing: The camera searches for the unique geometric patterns (AprilTags or high-contrast IR markers) on the landing pad protected by the Electrodynamic Dust Shield (EDS). The Jetson Nano calculates the "Pixel Error" between the center of the camera and the center of the pad.The Descent Funnel: The drone descends in a narrow "funnel," constantly adjusting its pitch and roll to keep the pixel error at zero.Magnetic Engagement: At 10cm altitude, the AI sends a final MAVLink command to "Land." Simultaneously, the base station electromagnets engage, pulling the drone into the final aligned position for induction charging.

5. Topic 4: Resonant Electromagnetic Induction Charging:

Power acquisition is the most volatile variable in Martian UAV operations. Traditional contact-based charging is prone to failure due to the abrasive, non-conductive nature of Martian dust (regolith). Project Kalinga bypasses this via a Resonant Wireless Power Transfer (WPT) system, engineered to function amidst the extreme electromagnetic (EM) background of the Martian surface.

5.1 Physics of Resonant Wireless Power Transfer (WPT):

Unlike standard inductive charging, which requires near-perfect physical contact, Project Kalinga utilizes Magnetic

Resonant Coupling. By tuning the LC (Inductor-Capacitor) circuits of the transmitter (base station) and receiver (drone legs) to a specific resonant frequency (150 kHz), we achieve high-efficiency energy transfer across a 10cm air gap.High-Radiation Resilience: Mars lacks a global magnetic field, exposing the surface to EM radiation $40\text{--}50$ times higher than Earth. To prevent this radiation from inducing "noise" or eddy currents in our charging field, the system uses High-Q Factor Resonators. These narrow-band resonators only accept energy at the specific programmed frequency, effectively filtering out the broad-spectrum solar and cosmic EM interference.Flux Concentration: To maximize efficiency through the thin, CO2-rich atmosphere, the coils are backed by Flexible Ferrite Sheets. These sheets steer the magnetic flux lines toward the receiver, preventing energy leakage into the Carbon Fiber frame, which could otherwise cause structural heating.

5.2 Bi-Directional Hardware Voltage/Current Sensor Integration

To provide ArduPilot with accurate telemetry, the Power Distribution Network (PDN) integrates a Bi-Directional Hall-Effect Current Sensor (ACS712-20A).Current Vectoring: Standard sensors only track discharge. Our integration detects the Polarity of the Current. When the induction coils are active, the current flows "backwards" into the battery.Radiation Shielding: Because Mars' high EM radiation can induce "phantom" voltages in analog sensor wires, the ACS712 is enclosed in a Faraday Cage made of Mu-metal. The signal is converted to digital via an I2C ADC (Analog-to-Digital Converter) immediately at the sensor source to ensure the "Charge" signal remains "clean" as it travels to the NVIDIA Jetson Nano.

5.3 Software-Level Charging Estimation (Percentage Calculation)

Voltage-based battery estimation fails on Mars because the extreme cold causes "Voltage Sag," making a half-full battery look empty. Project Kalinga utilizes Coulomb Counting processed by the Jetson Nano.The Algorithm: The Jetson Nano integrates the current over time ($Q = \int I \, dt$). By knowing the total capacity (4500 mAh), the software calculates the exact state of charge (SoC) regardless of the external temperature.ArduPilot Integration: The calculated percentage is pushed to ArduPilot via the BATTERY_STATUS MAVLink message. By sending a Negative Current Value, the ArduPilot Ground Control Station (Mission Planner) automatically identifies the drone is in "Charging Mode," allowing the operator to monitor the 3D map data transfer simultaneously.

5.4 Thermal Heat Dissipation during High-Current Charge Cycles

Fast-charging at 15.2V generates significant heat. In the near-vacuum of Mars, there is no air to carry heat away via convection; heat only moves via Conduction and Radiation.Pyrolytic Graphite Heat Spreaders: The induction coils are bonded to ultra-thin graphite sheets. These sheets have high lateral thermal conductivity, spreading the "Hot Spot" of the coil across the entire surface area of the Carbon Fiber landing gear.The Structural Radiator: The Carbon Fiber frame itself acts as a massive thermal radiator. By conductively coupling the charging electronics to the 3K Twill frame, we dissipate heat into the -60°C Martian environment via Infrared Radiation. This prevents the battery cells from reaching the critical 45°C threshold, where they would otherwise become unstable and degrade.

Suggested Additions and Changes for Mars Environment

- **Radiation Hardening of the "Cognitive Brain" (Jetson Nano):**
  The NVIDIA Jetson Nano uses 20nm process technology, which is susceptible to Single Event Upsets (SEU) when struck by high-energy cosmic rays.Physical Shielding: The Jetson Nano enclosure should be lined with a 0.5mm Tantalum or Lead-epoxy layer. This high-Z material acts as a sacrificial barrier to attenuate solar particle events (SPEs).Software Redundancy: Implement Watchdog Timers and ECC (Error Correction Code) emulation. If a radiation hit flips a bit in the "Small Square" coordinate memory, the system should perform a "triple-modular redundancy" check—comparing three stored instances of the coordinate and picking the majority.
- **Magnetic Interference Mitigation (10cm Docking Zone):**
  Since the drone relies on a 10cm magnetic grab, the resulting field is immense.Compass Suppression: On Earth, we use a magnetometer for heading. On Mars, between the crustal magnetism and your docking magnets, the compass will "flatline."The Change: Your report should specify that the ArduPilot MAG_ENABLE parameter is set to 0 during the final 2-meter approach. Navigation must switch entirely to Visual-Inertial Odometry (VIO) to prevent the magnets from spinning the drone out of control.
- **Electrostatic Discharge (ESD) Protection:**
  The dry, high-radiation Martian air causes the carbon fiber frame to build up a massive static charge during flight.The Risk: When the drone touches the base station, a high-voltage spark could jump, frying the Jetson Nano's USB or UART ports.The Fix: Add TVS (Transient Voltage Suppressor) Diodes to every data line between the induction coils and the main board. Ensure the carbon fiber frame is "common grounded" to the negative terminal of the battery to dissipate static safely into the landing pad.
- **Atmospheric Density Compensation:**
  Motor KV Selection: To fly in 1% density, you cannot use standard "Earth" motors.The Change: The report should specify Low-KV, High-Voltage (6S-8S) motors paired with thin-profile, high-pitch carbon fiber blades. This allows the drone to reach the 3,000+ RPM necessary to generate lift in the thin CO2 atmosphere.5. Optical Path ProtectionThe $40\text{--}50\text{x}$ UV radiation will degrade standard plastic camera lenses within weeks, turning them "cloudy."The Fix: Specify the use of Sapphire Glass or Fused Silica covers for the camera and LiDAR windows. These materials are UV-stable and scratch-resistant against the high-velocity Martian dust.

6. Topic 5: Magnetic Docking & Precise Alignment:

The transition from active flight to a static, charging state is the most mechanically demanding phase of the Project Kalinga mission. To achieve a 10cm docking window on the unpredictable Martian surface, the UAV utilizes a hybrid of high-energy electromagnetics and self-centering mechanical geometry.

6.1 Electromagnet Attraction Force Modeling (The 10cm Radius)The docking system relies on a "Capture Zone" defined by the inverse-cube law of magnetic attraction. At 10cm altitude, the base station activates four high-gradient electromagnets.Force Calculation: The attraction force (F) is modeled to overcome the maximum expected Martian wind shear (30 m/s). We utilize the formula:$$F = \frac{3\mu_0}{2\pi} \frac{m_1 m_2}{r^4}$$where m_1 and m_2 are the magnetic moments of the base and the drone's landing "feet."The "Soft Capture": To prevent a high-velocity impact that could crack the Carbon Fiber arms, the Jetson Nano utilizes PWM (Pulse Width Modulation) to ramp up the magnetic strength. This creates a "controlled pull" that guides the drone into the center of the charging pad rather than a violent "snap."

6.2 Mechanical Coupling: V-Groove Landing Leg Design While magnets provide the "pull," the mechanical design ensures "alignment." Even with $40\text{--}50\text{x}$ EM radiation causing potential sensor noise, the physical shape of the drone guarantees a perfect docking connection.V-Groove Geometry: The landing legs are engineered with a 60-degree V-Groove profile. When the magnets pull the drone down, any lateral misalignment (up to 5cm) is corrected as the legs "slide" into the corresponding inverse grooves on the base station.Kinematic Coupling: This 3-point or 4-point kinematic mount ensures that the Resonant Induction Coils are aligned with sub-millimeter precision. This precision is vital for maintaining high-efficiency power transfer $(>85\%)$ and enabling high-speed WiFi-6 data bursts without signal scattering.

6.3 Electromagnetic Interference (EMI) Mitigation and Shielding The intense magnetic field required for a 10cm grab, combined with the extreme solar radiation on Mars, creates a "noisy" environment that can destroy sensitive CSE hardware like the NVIDIA Jetson Nano.Mu-Metal Enclosures: The Jetson Nano and the ArduPilot Orange Cube+ are housed in a dual-layer shield. The inner layer is Aluminum (for high-frequency RF shielding), and the outer layer is Mu-metal (a nickel-iron alloy with extremely high magnetic permeability) to divert the low-frequency magnetic flux away from the CPU and storage.Twisted-Pair Data Lines: All internal communication lines (UART/I2C) are shielded twisted pairs. This prevents the "Capture Magnets" from inducing "Ghost Currents" in the wires, which could otherwise cause the Jetson Nano to interpret a docking pull as a "Software Command."

6.4 Sensor Suppression: Disabling Magnetometers during the "Grab" PhaseUnder normal flight conditions, ArduPilot uses a Magnetometer (Compass) to determine heading. However, within the 10cm docking zone, the compass becomes a liability.Magnetic Saturation: The docking magnets produce a field strength that exceeds the Earth-standard magnetometer's range (4.7 Gauss). If left active, the EKF3 (Extended Kalman Filter) would perceive a "Magnetic Anomaly," causing the drone to spin wildly in a desperate attempt to correct its heading.The "Suppression" Protocol: At the $2\text{--}\text{Meter Transition}$, the Jetson Nano sends a MAVLink override to ArduPilot to switch the EK3_MAG_I_GATE to zero.VIO-Only Navigation: For the final 10cm, the drone is "Compass Blind" but "Visual Aware." It relies 100% on Visual-Inertial Odometry (VIO) and the YOLOv8-Nano visual detection of the docking pad. This ensures the drone remains steady while the magnets pull it into the final "locked" position.Suggested Addition for Mars Environment: Radiation-Hardened ConnectorsStandard plastic connectors will become brittle and "outgas" in the Martian vacuum and high UV/EM radiation. For Project Kalinga, all external connections between the landing legs and the main frame must use PEEK (Polyether ether ketone) or Ceramic-insulated connectors. These materials are tested to survive $40\text{--}50\text{x}$ Earth's radiation levels without losing their structural or electrical properties.

7. **Topic 6: Triple-Layer Communication Stack**The communication architecture of Project Kalinga is designed to overcome the extreme atmospheric and electromagnetic interference of the Martian surface. By utilizing a "Triple-Layer" redundancy model, the UAV ensures that critical telemetry is never lost, even when high-bandwidth data is restricted by distance or dust storms.

7.1 Layer 1: LoRa Sub-GHz Survival Telemetry (SX1262): The foundation of the communication stack is the Semtech SX1262 LoRa module. Operating in the sub-GHz band (configured to $868/915\text{ MHz}$), this layer serves as the "Survival Heartbeat" of the drone.Propagation Resilience: Low-frequency signals are far more effective at penetrating the fine, iron-rich Martian dust than high-frequency Wi-Fi. LoRa provides a reliable link up to 10–15 km across the flat regolith.Low-Power Telemetry: This layer transmits essential MAVLink packets: Battery Voltage, GPS-relative "Small Square" coordinates, and AI Health Status. Because the bitrate is low (approx. 22 kbps), the power consumption is negligible, allowing the drone to maintain a "safety line" even if the main batteries are critical.Radiation Hardening: The SX1262 is configured with a high Coding Rate (CR 4/8), adding significant forward error correction to protect packets from being corrupted by the $40\text{--}50\text{x}$ higher cosmic radiation levels.

7.2 Layer 2: ESP-NOW Tactical Low-Latency Link (1km Range): As the drone approaches within 1 km of the base station, the tactical layer—ESP-NOW—activates. ESP-NOW is a connectionless protocol developed by Espressif that runs on the 2.4 GHz band but bypasses the heavy overhead of traditional Wi-Fi.Zero-Handshake Latency: Unlike Wi-Fi, which requires a time-consuming "association" process, ESP-NOW allows the NVIDIA Jetson Nano to send navigation updates to the base station instantly.Tactical Precision: This layer handles the high-frequency "Vision-Position-Estimate" (VPE) updates needed for the precision approach. It allows the base station to track the drone’s descent with millisecond accuracy, ensuring the AI can adjust for sudden Martian wind gusts in real-time.

7.3 Layer 3: WiFi 6 High-Speed Map Data Payload (600+ Mbps): The final layer is the WiFi 6 (802.11ax) protocol, which is reserved strictly for high-capacity "Data Bursts" once the drone is within the 10cm magnetic docking zone.The Map Dump: After a 15-minute flight, the Jetson Nano has accumulated hundreds of megabytes of 3D point-cloud data. Transferring this over LoRa or ESP-NOW is impossible. WiFi 6 provides the 600+ Mbps throughput required to move the entire 3D map to the base station in under 10 seconds.OFDMA for EM Noise: WiFi 6 utilizes Orthogonal Frequency Division Multiple Access (OFDMA). This allows the signal to "hop" around the specific frequencies being jammed by the Induction Charging Coils or the background Solar Radiation, maintaining a stable high-speed link during the charging cycle.

7.4 Invisible Antenna Design: PCB Trace and Ceramic Chip Implementation: To maintain the aerodynamic integrity of the Carbon Fiber S500 frame and ensure no "snag points" during the 10cm magnetic grab, Project Kalinga utilizes an Antenna-less (internalized) design.Ceramic Chip Antennas: For the 2.4 GHz (ESP-NOW) and 5.8 GHz (WiFi 6) bands, we utilize Dielectric Ceramic Chip Antennas. These are surface-mounted directly onto the PCB, measuring only a few millimeters. They are immune to the physical vibration of the high-RPM Martian motors and are shielded from UV degradation by the drone's outer shell.PCB Trace Antennas: The LoRa system uses a Meandered Inverted-F Antenna (MIFA) etched directly into the copper layer of the PCB. This eliminates the need for a "whip" antenna that could be snapped off during a rough landing or interfered with by the 10cm docking magnets.Radiation-Stable Substrates: All PCBs use Rogers 4350B or high-TG FR4 substrates, which do not "outgas" in the thin Martian atmosphere and maintain their dielectric constant despite the $40\text{--}50\text{x}$ increased EM radiation exposure.Suggested Addition for Mars Environment: The "Faraday-Switch" LogicA unique challenge of the 10cm docking zone is that the Electromagnets and Induction Coils generate a massive localized EM field that can "blind" the WiFi 6 receiver.The Change: Include a software logic where the Jetson Nano coordinates the "Data-Power Interleave." The system pauses the high-power induction for 500ms every few seconds to allow a "Clear Window" for a high-speed WiFi data burst. This prevents the charging field from corrupting the 3D map data transfer.

8. Topic 7: Ground Control Station (GCS) & Monitoring:

The Ground Control Station (GCS) serves as the primary interface for mission oversight and data visualization. For Project Kalinga, the standard terrestrial GCS must be transformed into a planetary command center capable of interpreting AI-generated 3D coordinates and handling high-bandwidth "Map Bursts" across the triple-layer communication stack.

8.1 Mission Planner Customization: Custom Map Provider OverlaySince standard satellite imagery (Google/Bing Maps) lacks the sub-meter resolution required for 10cm-grid navigation, ArduPilot Mission Planner is modified to use a Dynamic Custom Map Provider.The Voxel-to-Pixel Pipeline: As the NVIDIA Jetson Nano discovers new "Small Squares" on the Martian surface, it generates a localized 2D Topographic Map (Orthomosaic). This image is tiled and "injected" into Mission Planner using a custom Python script.Grid Synchronization: The GCS interface displays a high-contrast grid overlay. Each square in Mission Planner corresponds to a physical $10\text{cm} \times 10\text{cm}$ coordinate in the drone's AI memory. This allows the operator to see the "Discovery Progress" in real-time as the drone paints the map white (explored) vs. black (unexplored).Coordinate Offsets: To handle the $40\text{--}50\text{x}$ higher EM radiation and the lack of a global magnetosphere, the GCS ignores "Global GPS" and instead centers the map on the Inductive Base Station at coordinate $(0, 0)$.

8.2 Live Video Integration using GStreamer via WiFi 6 Visual verification is essential for monitoring the "10cm Magnetic Grab" and the Electrodynamic Dust Shield (EDS) performance. We utilize a GStreamer pipeline optimized for the low-latency capabilities of WiFi 6.Low-Latency H.265 Stream: The Jetson Nano encodes the 1080p/60fps camera feed using the hardware-accelerated NVENC engine. This stream is "piped" through a UDP port to the GCS.The Mission Planner HUD: The live feed is integrated directly into the Mission Planner HUD (Heads-Up Display). This allows the operator to see through the "Eyes of the AI," observing how the YOLOv8-Nano model identifies the landing pad markers through the Martian haze.Bandwidth Management: To prevent video from interfering with the "3D Map Dump," the GCS automatically drops the video resolution to 480p once the drone enters the 10cm docking zone, prioritizing data integrity over visual clarity.

8.3 Real-time Data Transfer Monitoring (HUD Progress Bars) Monitoring the transfer of the high-fidelity 3D map is critical to ensure the drone doesn't undock before the data is secured.MAVLink Progress Injection: The Jetson Nano calculates the percentage of the current "Map Burst" completed. This is sent to the GCS via the NAMED_VALUE_FLOAT MAVLink message.Visual HUD Overlays: We utilize the Mission Planner "User Items" feature to create a persistent progress bar on the flight screen.Telemetry Bar: Shows the health of the LoRa/ESP-NOW links.Sync Bar: Shows the percentage of the 3D point-cloud successfully moved to the base station.Alert Logic: If the data transfer stalls due to EM noise from the induction coils, the HUD triggers a "Red Flash" alert, and the docking magnets are held in the "Locked" state to prevent accidental takeoff.

8.4 MAVProxy Terminal Integration for Advanced Telemetry Logging For a professional CSE-grade system, Mission Planner is supplemented by MAVProxy, a command-line GCS that provides a deeper "Under-the-Hood" view of the mission.The Developer Terminal: MAVProxy runs in a Linux terminal alongside the map. It logs every raw MAVLink packet from the

$40\text{--}50\text{x}$ radiation-hardened electronics, allowing for post-mission "Black Box" analysis.Custom Modules: We have developed a MAVProxy module called Kalinga_Monitor.py. This script monitors the Signal-to-Noise Ratio (SNR) of the LoRa link. If the SNR drops below a safe threshold (indicating a solar flare or dust storm), MAVProxy automatically issues an "Emergency Land" command.Asynchronous Logging: While Mission Planner handles the "Visuals," MAVProxy handles the "Payload." It receives the raw binary chunks of the 3D map and assembles them into a .PLY or .OBJ file on the base station's local NVMe drive.Suggested Addition for Mars Environment: The "Radiation Event" LogDue to the constant bombardment by GCRs (Galactic Cosmic Rays), the GCS should include a specific "Bit-Flip Counter." * The Change: Whenever the Jetson Nano's Triple-Modular Redundancy (TMR) detects a memory mismatch, it sends an interrupt to the GCS.The Fix: A dedicated window in MAVProxy logs the frequency of these "Radiation Events." This data is vital for assessing the health of the 0.5mm Tantalum shielding and predicting the remaining operational lifespan of the drone's memory modules.

9. Topic 8: Environmental Hardening for Mars Surface:

The final layer of the Project Kalinga design addresses the physical realities of the Martian frontier. Operating a UAV in a near-vacuum, high-radiation, and cryogenic environment requires engineering solutions that transcend standard terrestrial robotics. This section details the "Hardening" protocols that ensure the NVIDIA Jetson Nano and Carbon Fiber S500 airframe survive the Martian Sol.

9.1 Atmospheric Modeling: Rotor RPM and Lift at 1% Density

Generating lift on Mars is an exercise in extreme aerodynamics. With an atmospheric density of approximately 0.020 kg/m^3 (roughly 1% of Earth's), the fluid dynamics of flight shift into a high-Mach, low-Reynolds number regime.The Lift Equation Challenge: To maintain a hover, the rotors must move a massive volume of air at high velocity. We utilize thin-profile, high-pitch Carbon Fiber Propellers optimized for CO2 gas.RPM Scaling: While an Earth-based S500 drone hovers at $\sim 1,500 \text{ RPM}$, Project Kalinga is geared for 3,500–4,000 RPM. This requires Low-KV (e.g., 100-150 KV) high-voltage motors to maintain torque without overheating the windings in the thin air, which provides poor convective cooling.Tip Speed Constraints: At these high RPMs, the propeller tips approach the local speed of sound ($c \approx 240 \text{ m/s}$ on Mars). The AI-controller is programmed to cap the throttle to prevent "transonic flow separation," which would lead to a catastrophic loss of lift.

9.2 Electrostatic Dust Repulsion for Optical LensesMartian dust is not just an abrasive; it is a dielectric hazard. Due to constant UV exposure and the lack of humidity, dust particles carry a significant electrostatic charge, causing them to "glue" themselves to the camera and LiDAR lenses.Electrodynamic Dust Shield (EDS): All optical windows (Sapphire Glass) are embedded with transparent Indium Tin Oxide (ITO) electrodes.The Clearing Cycle: Before the 2-Meter

Transition for docking, the Jetson Nano activates a high-voltage, low-current traveling wave across these electrodes. This creates an alternating electric field that "flicks" the charged dust particles off the lens, ensuring the YOLOv8-Nano model has a 99% clear view of the AprilTags.

9.3 Thermal Budget: Calculating the "Heating Tax" for ElectronicsOn Mars, the "Heating Tax" is the most expensive part of the energy budget. During the Martian night, temperatures drop to -100°C, which would freeze the electrolyte in the LiPo batteries and shatter the silicon in the Jetson Nano.Thermal Insulation: The core electronics are encased in Silica Aerogel, the world’s lightest and most effective thermal insulator.Survival Heating: We reserve 30% of the total battery capacity exclusively for "Survival Heating." Integrated polyimide resistive heaters are triggered by ArduPilot when the internal temperature drops below -10°C.Radiative Balance: During the day, the 40-50x higher solar radiation threatens to overheat the CPU. The carbon fiber frame is utilized as a "Cold Plate," conductively wicking heat away from the Jetson Nano and radiating it as IR energy into the environment.

9.4 Conclusion and Future Scaling of Project Kalinga: Project Kalinga represents a shift from "Remote Control" to "Planetary Autonomy." By combining the high-level cognitive power of the NVIDIA Jetson Nano with the reflexive stability of ArduPilot, we have designed a system capable of mapping the unknown without the crutch of GPS.Summary of Innovation: The integration of a 10cm magnetic docking window, resonant induction charging, and a triple-layer radiation-hardened communication stack provides a blueprint for sustainable long-term exploration.Future Scaling: The next phase of Project Kalinga involves Swarm Intelligence. Using the "Small Square" grid logic established here, multiple UAVs can share a unified 3D coordinate system, allowing a fleet of drones to map entire Martian craters in a fraction of the time.Final Statement: As we move toward a multi-planetary future, the technologies developed for Project Kalinga—from electrostatic dust repulsion to autonomous VIO navigation—will serve as the foundational "Eyes and Ears" for the first generation of Martian settlers.

For more information
Please visit our Website - https://kalinga.space/