

Onboard Edge Computing for High-Resolution FMCW SAR on An Integrated UAV Platform

ECE 445 Design Document

Team 12

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1 Introduction

1.1 Problem and Solution Overview:

Recent advances in unmanned aerial vehicles (UAVs) have enabled compact remote sensing platforms for applications such as terrain mapping, disaster monitoring, and infrastructure inspection. Among these, frequency-modulated continuous-wave synthetic aperture radar (FMCW SAR) offers a compelling solution due to its low power consumption, lightweight hardware requirements, and capability for high-resolution imaging independent of lighting and weather conditions. Prior work within our group has demonstrated the feasibility of a UAV-mounted FMCW SAR system integrated with commercial drone platforms. However, these implementations suffered from several limitations, including suboptimal imaging quality, sensitivity to motion errors, hardware integration challenges, and the reliance on offline processing for SAR image formation. As a result, the system was not able to provide reliable or real-time situational awareness, which significantly restricts its practical applicability in time-critical scenarios.

This project aims to address these limitations by redesigning both the hardware and computational pipeline of the UAV-based FMCW SAR system. On the hardware side, improvements in platform integration, power management, and RF front-end design are expected to enhance signal quality and system stability. On the algorithmic side, more advanced SAR processing techniques and motion compensation methods will be implemented to improve image resolution and robustness. Most importantly, leveraging modern high-performance embedded computing platforms, this project seeks to transition SAR image formation from offline post-processing to real-time onboard computation, enabling immediate visualization on the drone controller. Compared to previous implementations, the proposed system is expected to deliver significantly improved imaging quality, higher system reliability, and real-time operational capability, representing a substantial step toward practical UAV-borne SAR deployment.

1.2 Visual Aid:

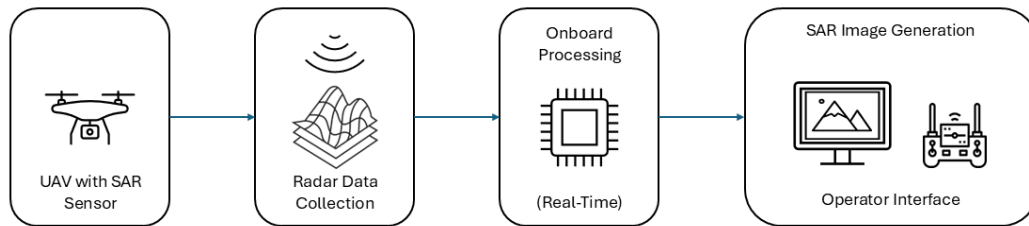


Figure 1: Conceptual Overview of Real-Time SAR Imaging with Onboard Processing

1.3 High-level Requirements List:

- The system shall acquire radar return signals maintaining a minimum signal-to-noise ratio (SNR) of 5 dB, with a data packet loss rate of less than 1% along the flight path.
- The system must be capable of generating two-dimensional SAR images with a meter-level resolution and sufficient contrast to distinguish basic scene features.
- The system must perform onboard processing and transmit SAR images to the ground controller with an end-to-end latency of no more than 5 seconds per frame.

2 Design

2.1 Block Diagram

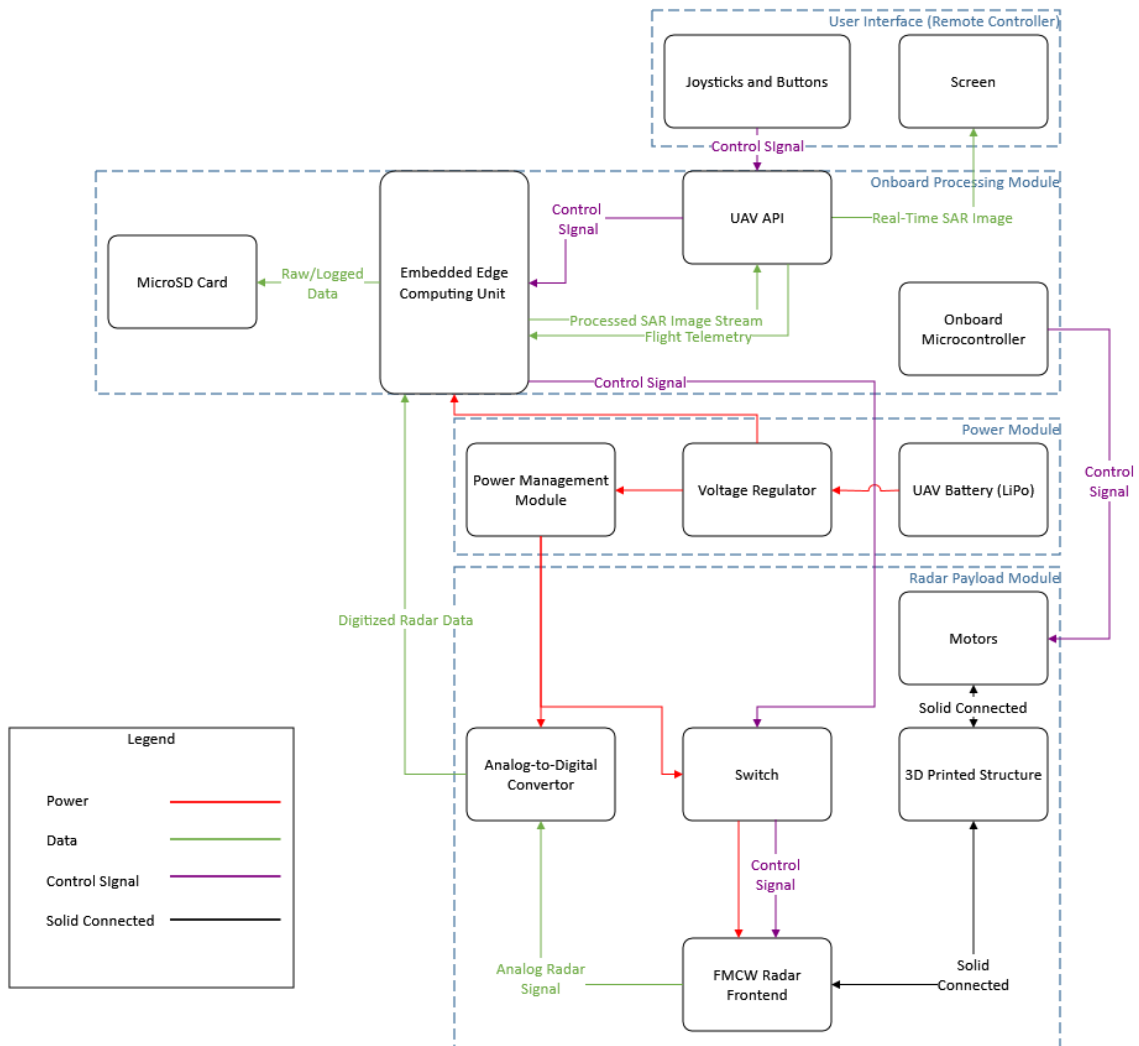


Figure 2: The Block Diagram of the Whole System

2.2 Subsystem Descriptions

The overall system is divided into four main subsystems: the RF sensing subsystem, the signal acquisition subsystem, the onboard processing subsystem, and the communication and control subsystem. A power management module supports all subsystems by providing regulated power from the UAV platform. This system structure follows typical UAV-based SAR architectures [1].

2.2.1 RF Sensing Subsystem

The RF sensing subsystem is responsible for transmitting and receiving radar signals. It consists of an FMCW radar module and antenna components. The subsystem generates frequency-modulated continuous wave signals and transmits them toward the target area [2]. Reflected signals from objects in the environment are received by the antenna and passed to the signal acquisition subsystem as analog radar signals.

The performance of this subsystem directly affects the quality of the collected data. Factors such as signal strength, antenna configuration, and noise levels influence the accuracy and resolution of the final SAR image. The analog radar output is directly interfaced with the signal acquisition subsystem, forming the first stage of the processing pipeline. At the current stage, the subsystem design has been finalized and is being integrated with the fabricated casing for testing.

Requirement	Verification
FMCW radar signals are generated for transmission.	Validate transmitted signal characteristics using reference measurements.
Radar signals are transmitted toward the target.	Verify signal transmission using test measurements.
Reflected signals from the environment are received by the antenna.	Confirm reception of reflected signals under controlled conditions.
Analog radar signals are provided to the signal acquisition subsystem.	Verify signal transfer between radar module and acquisition subsystem.

Table 1: RF Sensing Subsystem Requirements and Verification

2.2.2 UAV and Remote Control Subsystem

The DJI Pilot2 application will be used to set a predefined flight course of the drone using its “Mission Flight” functionality [3]. A DJI Extension Board is employed for easier configuration between the third-party development board and the port provided by the drone. This board is connected to the processing unit through UART and network ports, enabling data exchange and

control signal transmission.

This subsystem provides flight trajectory control and UAV motion data, which may be used by the onboard processing subsystem to improve imaging accuracy. It also ensures stable UAV operation and sufficient power supply to the radar and processing systems. At the current stage, communication interfaces have been established and are being prepared for integration and testing.

Requirements	Verification
The app can control the drone to fly along a user-defined course.	Carry out some flights with the course planning feature and verify if the planned courses match with actual courses.
When the drone is flying along the course, it can maintain a certain yaw angle so the antenna can face the desired direction.	Test a variety of courses and check the feedback data.
The processing unit can communicate with the UAV platform successfully.	Verify successful communication between the processing unit and UAV platform by retrieving UAV position data.
The UAV platform can supply sufficient power to the radar and processing system.	Check the manual of UAV and Orin nano, and the design of radar to compare the power supply ability and consumption.

Table 2: Merged requirements and verification table.

2.2.3 Signal Acquisition Subsystem

The signal acquisition subsystem converts the received analog radar signals into digital data for processing. It includes signal conditioning components and an analog to digital converter (ADC).

Incoming signals from the RF sensing subsystem are first amplified and filtered to reduce noise and improve signal quality. The conditioned signal is then sampled by the ADC to produce a digital representation suitable for further processing. The digitized data is transmitted to the onboard processing subsystem for SAR image reconstruction. The accuracy of this

subsystem is important, as errors in sampling or signal degradation will directly impact the performance of the onboard processing subsystem.

Stable power from the power management module is required to ensure reliable signal conversion. At the current stage, the acquisition pipeline has been designed and is being prepared for integration with the radar frontend and processing unit.

Requirement	Verification
Incoming radar signals are filtered and amplified to improve signal quality.	Compare signals before and after conditioning to confirm improvement.
Noise in the received signal is reduced prior to sampling.	Evaluate signal-to-noise ratio before and after filtering.
Analog radar signals are converted into digital data using an ADC.	Compare analog input and digital output to verify accurate conversion.
Digitized data is transferred to the onboard processing subsystem.	Verify successful data transmission to the processing unit.
Stable power is maintained to ensure reliable signal conversion.	Measure voltage stability during operation.

Table 3: Signal Acquisition Subsystem Requirements and Verification

2.2.4 Onboard Processing Subsystem

The onboard processing subsystem performs real-time SAR data processing on the UAV, where reflected radar signals are reconstructed into images based on SAR imaging principles [4]. This subsystem is the main focus of the project, as it enables immediate image generation without relying on offline computation.

The subsystem receives digitized radar data from the signal acquisition subsystem and may incorporate UAV motion data to improve imaging accuracy. The processing pipeline includes signal preprocessing, Fourier transform operations, and SAR image reconstruction algorithms such as the Range Migration Algorithm (RMA). The processed output is a two-dimensional SAR image that represents the scanned environment and is transmitted to the communication subsystem for visualization.

By implementing processing onboard, the system reduces latency and allows for faster feedback compared to traditional SAR systems. At the current stage, the processing pipeline has been validated in simulation and is being implemented on the embedded platform.

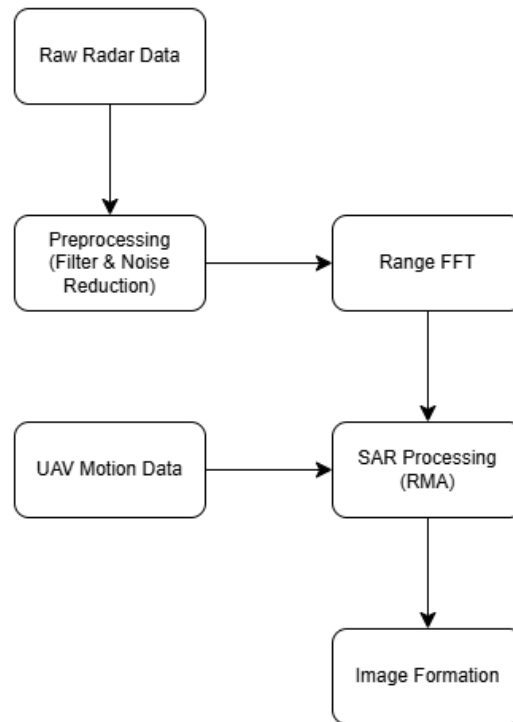


Figure 3: Onboard Processing Pipeline for Real-Time SAR Image Generation

Requirement	Verification
Radar data is preprocessed to reduce noise and prepare it for further processing.	Compare preprocessed data with raw input to confirm noise reduction.
Fourier transform-based range processing is applied to the digitized data.	Validate FFT output against expected frequency-domain results.
SAR image reconstruction is performed using the RMA.	Compare generated images with simulation or reference outputs.
UAV motion data is incorporated to improve imaging accuracy.	Compare results with and without motion data to verify improvement.
SAR images are generated in real time within onboard computational constraints.	Measure processing latency and monitor system resource usage.

Table 4: Onboard Processing Subsystem Requirements and Verification

2.2.5 Communication and Control Subsystem

The communication and control subsystem manages data transmission and system coordination between the UAV and the operator. It utilizes the UAV platform interface, such as the DJI SDK, to send processed data and receive control inputs.

Once the SAR image is generated, it is transmitted to the ground station or remote controller for visualization. The operator can also adjust system parameters through control commands. This subsystem ensures coordinated system operation and supports real-time interaction during flight.

It interfaces directly with the onboard processing subsystem for data transmission and with the UAV platform for control and telemetry exchange. At the current stage, communication functions are being integrated and prepared for system-level testing.

Requirement	Verification
Processed SAR images are transmitted to the user interface for visualization.	Verify successful image display on the remote controller.
Control inputs from the operator are received and processed by the system.	Confirm system response to user commands.
Reliable communication is maintained between the UAV and onboard processing unit.	Test consistency and reliability of data transmission.
Integration with the UAV platform interface (e.g., DJI SDK) is supported.	Validate system operation through the UAV control framework.

Table 5: Communication and Control Subsystem Requirements and Verification

2.2.6 3D Printed Physical System

The physical enclosure system consists of two custom-designed 3D printed components that support the integration of the SAR sensing hardware, onboard computing system, and UAV mounting structure. The lower enclosure section provides a rigid mechanical interface between the gimbal assembly and the SAR antenna module while also housing the onboard processing hardware, including the NVIDIA Jetson Orin Nano development board. The detachable cover design allows easier access to the RF circuitry and internal components for assembly, maintenance, debugging, and future hardware modifications. Because the wiring length between the gimbal system and onboard processor is limited, the enclosure layout was designed to keep these components in close proximity while maintaining stable cable routing and structural support during UAV operation.



Figure 4: 3D Printed Physical Enclosure

Compared to the previous design iteration, several modifications were introduced to improve structural reliability and hardware integration. The enclosure wall thickness was increased to improve mechanical strength and durability under vibration and movement during flight operations. The internal dimensions of the enclosure were also adjusted to ensure sufficient clearance for the NVIDIA Jetson Orin Nano development board and related electrical components. In addition, the mounting and screw hole locations were redesigned to better accommodate the updated assembly requirements and improve fastening alignment between the enclosure sections and internal hardware.

The external dimensions of the enclosure were further refined to ensure compatibility with the UAV mounting interface and gimbal support structure. These adjustments allow the enclosure to be securely mounted onto the UAV platform while maintaining proper positioning of the SAR sensing components. The design also considers accessibility for assembly and maintenance by separating the structure into detachable sections for easier installation of the RF circuitry and onboard electronics.

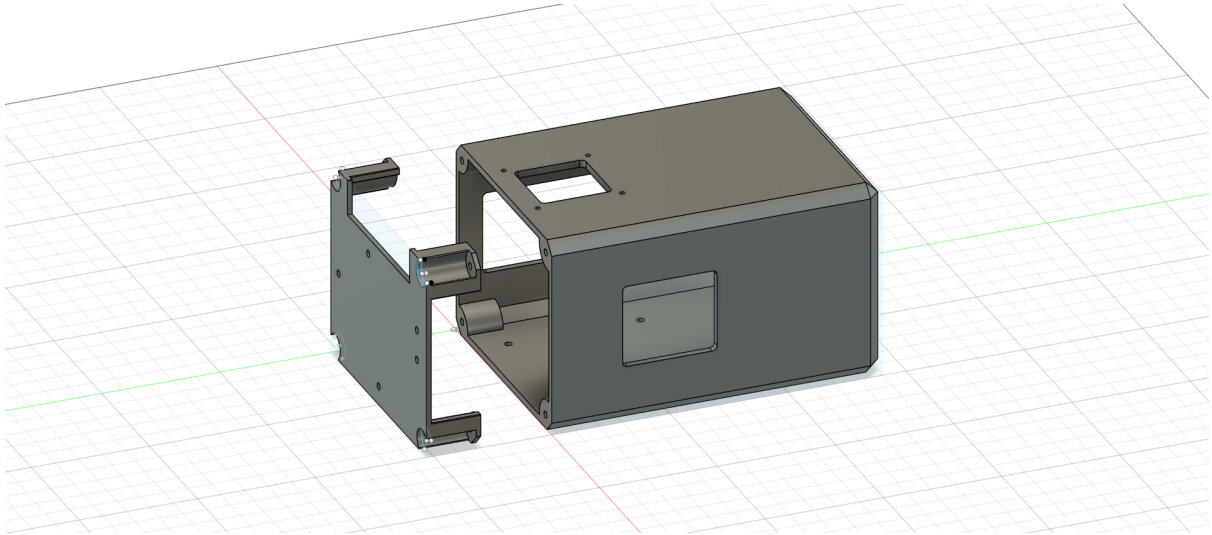


Figure 5: CAD Model of the Redesigned 3D-Printed Enclosure and Detachable Mounting Cover

All enclosure components are manufactured using 3D printing technology, which enables rapid prototyping, flexible dimensional modifications, and lightweight fabrication suitable for UAV deployment.

2.2.7 PCB design

The PCB contains a compact signal generation and conditioning system composed of three main functional blocks: a wave generator, a signal amplifier, and a regulated power supply.

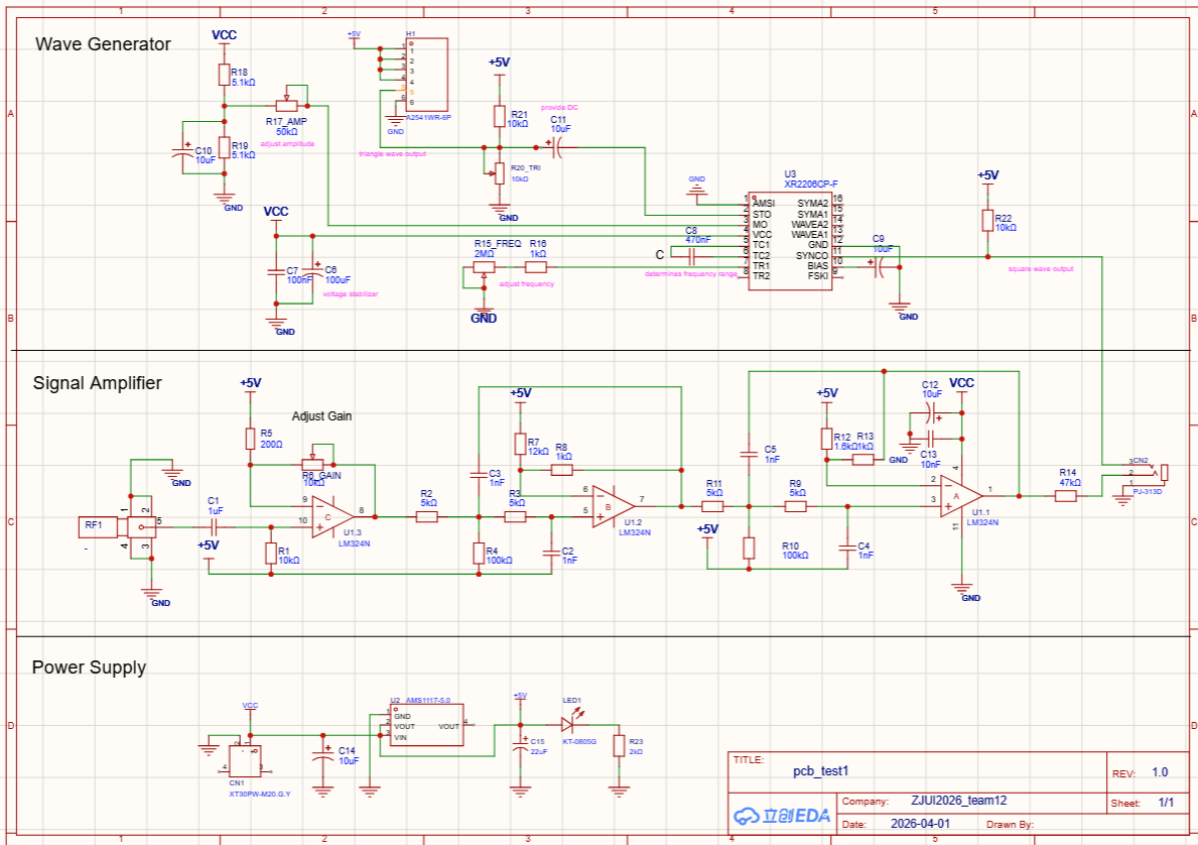


Figure 6: PCB schematic

The wave generator section produces multiple waveform types using a dedicated function generator IC (XR2206). External resistors and capacitors define the oscillation frequency and waveform characteristics, while adjustable components allow fine tuning of amplitude and frequency. The circuit provides both triangle and square wave outputs, with proper coupling capacitors and biasing networks ensuring stable signal generation.

The signal amplifier section uses multiple LM324 operational amplifiers to condition and amplify the generated signal. It includes stages for gain adjustment, filtering, and buffering. Passive components such as resistors and capacitors form feedback networks and frequency-shaping filters, enabling precise control over signal amplitude and bandwidth. The design supports adjustable gain and improved signal integrity for downstream applications.

The power supply section converts an external input voltage into a stable +5V supply using a linear voltage regulator (AMS1117-5.0). Decoupling capacitors are included to reduce noise and ensure stable operation, while an LED indicator provides a visual confirmation of power

status.

Overall, the circuit is designed to generate configurable waveforms and amplify them with controlled gain, making it suitable for signal testing, prototyping, and educational purposes.

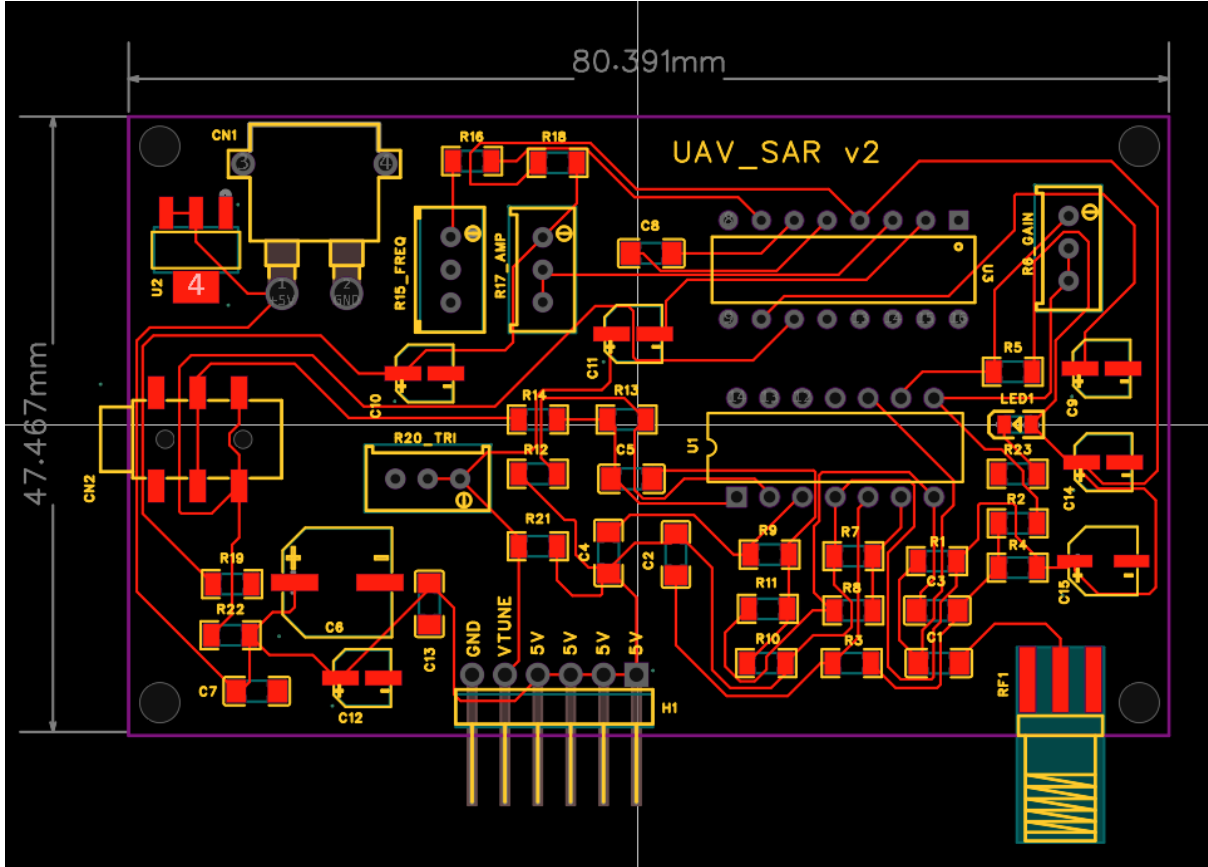


Figure 7: PCB design

For PCB design, we avoid using vias. This approach minimizes the parasitic inductance and capacitance typically introduced by vias, thereby reducing their impact on high-frequency signal integrity. As a result, signal distortion, reflection, and loss are effectively suppressed, ensuring improved performance and reliability for high-speed and high-frequency applications.

2.3 Tolerance Analysis

The baseline objective is to transition from an offline batch process to a continuous real-time pipeline capable of generating one SAR image frame per second. The system processes a sliding window of 10 seconds of historical radar data, sampled at 48 kHz with a pulse repetition frequency (PRF) of approximately 50 Hz, resulting in an image matrix of roughly 4000×2000

pixels after zero-padding.

Two primary SAR imaging algorithms were analyzed: the currently implemented fast approximation (ω -k or wKA algorithm) and the computationally demanding, high-fidelity Back-Projection Algorithm (BPA). For the ω -k algorithm, the computational complexity is dominated by a large 2D Inverse Fast Fourier Transform (IFFT). The combination of 1D FFTs, interpolation, and the final 4000×2000 2D IFFT requires approximately 1.1 GFLOPS per frame. In contrast, the BPA corrects for UAV turbulence by calculating the exact distance to every pixel ($2000 \times 2000 = 4,000,000$ pixels) for each of the 500 pulses in the 10-second window. Assuming approximately 25 floating-point operations (FLOPs) per pixel per pulse for distance calculation, interpolation, and phase multiplication, the total compute demand for BPA reaches approximately 50 GFLOPS per frame.

NVIDIA Jetson Orin Nano (8GB) provides a peak compute performance of 1,280 GFLOPS (1.28 TFLOPS) in FP32 and a memory bandwidth of 68 GB/s [5], the tolerance margins are highly favorable. The ω -k algorithm utilizes less than 0.1% of the available compute capacity, indicating that a GPU-accelerated implementation will execute the entire pipeline in milliseconds. Even the notoriously heavy BPA algorithm utilizes only around 4% of the Orin Nano's capacity. By heavily parallelizing the pixel calculations across the GPU cores, high-fidelity, motion-compensated SAR images can easily be generated in real-time.

3 Cost and Schedule

3.1 Cost Analysis

Labor cost: Assume that each of us costs ¥50/hour, the total construction period is estimated to be 120 hours. The total labor cost is calculated as:

$$\text{¥}50/\text{hr} \times 4 \times 120\text{hrs} = \text{¥}24000 \simeq \$3430 \quad (1)$$

manufacturing cost:

Category	Item Description	Est. Cost(RMB)
Edge Computing Platform	NVIDIA Jetson Orin Nano Developer Kit (8GB)	2500
	NVMe M.2 SSD	800
PCB & Electronics	PCB printing	30*3
	PCB components	150
	High-speed ADC/DAC chips (for radar baseband interface)	500
	Miscellaneous electronic components (Op-amps, LDOs, connectors)	100
Mechanical Structure	3D Printing Materials	200
	Vibration isolation mounts & hardware (screws, standoffs)	50
Total		4390

3.2 Schedule

Week	Yinfei Ma	Chenxiao Wang	Giselle	Victoria
03/30/2026	analyzing former works, design document writing	investigate imaging algorithms, design document writing	designing workflow, design document writing	proposal writing, design document writing
04/06/2026	flight test and control code learning	select imaging algorithm, simulation setup	preliminary mechanical design, CAD modeling	system architecture design, component selection
04/13/2026	implement basic flight control and data logging	implement basic SAR processing pipeline	modeling refinement, start prototyping	schematic design, PCB layout planning
04/20/2026	flight testing with basic trajectory, data collection	test imaging algorithm with collected/simulated data	3D printing and mechanical assembly	PCB design and initial fabrication
04/27/2026	improve flight stability and synchronization with radar	optimize imaging algorithm and processing speed	integrate mechanical structure with UAV platform	PCB assembly and component integration
05/04/2026	integrate flight control with full system	integrate real-time processing pipeline	finalize mechanical mounting and adjustments	system integration and debugging (power, signal)
05/11/2026	system-level testing and debugging	image quality improvement and validation	support system integration and testing	full system debugging and reliability testing
05/18/2026	final test	demo preparation	final test	demo preparation

4 Discussion of Ethics and Safety

This project involves the design and deployment of a UAV-mounted FMCW SAR system, which introduces several ethical and safety considerations related to aerial operation, electromagnetic emissions, data collection, and hardware risks. These concerns must be carefully addressed to ensure responsible development and safe operation.

4.1 Ethical Considerations

One primary ethical concern is related to data privacy and surveillance. SAR systems are capable of imaging objects regardless of lighting or weather conditions, which raises concerns about unintended monitoring of private property or individuals. To mitigate this, the system will be tested only in controlled environments (e.g., designated test fields or campus-approved areas) and will not be used to intentionally image individuals or private residences. All collected data will be used strictly for research and educational purposes and will not be distributed publicly without proper anonymization.

Another ethical consideration is responsible use of UAV technology. UAVs can pose risks to public safety if misused or improperly operated. All team members will follow institutional and local aviation regulations (e.g., FAA guidelines), and only trained operators will be allowed to control the UAV during experiments.

4.2 Safety Considerations and Mitigation Procedures

This project involves several high-risk components, including aerial vehicles, high-energy batteries, RF electronics, and onboard computing systems. The following safety measures are implemented:

1. UAV Operation Safety

- All flights will be conducted in open, controlled environments away from people, buildings, and restricted airspace.
- Pre-flight checklists will be used to verify system integrity (battery level, payload mounting, communication link, GPS status).

- A fail-safe mechanism (e.g., emergency landing) will be enabled at all times.
- A minimum safe distance (e.g., >10 meters) from personnel will be maintained during operation.

2. Electrical and Battery Safety

- Only manufacturer-approved batteries and power modules will be used.
- Batteries will be inspected for damage before use and will not be operated outside recommended voltage/current limits.
- Charging will be performed under supervision using certified chargers.
- Fire-resistant storage (e.g., LiPo safety bags) will be used when handling batteries.

3. RF and Electronic Safety

- The radar system will operate within low-power limits appropriate for laboratory and educational use.
- Proper shielding and grounding will be implemented to prevent unintended electromagnetic interference.
- All exposed wiring will be insulated and secured to prevent short circuits or accidental contact.

4. Mechanical and Integration Safety

- All onboard components will be securely mounted to prevent detachment during flight.
- Weight and balance constraints of the UAV platform will be strictly observed.
- Cable management will be implemented to avoid interference with propellers or moving parts.

5 Citations

References

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