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

ECE 445 Design Document

Team 12

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Contents

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:

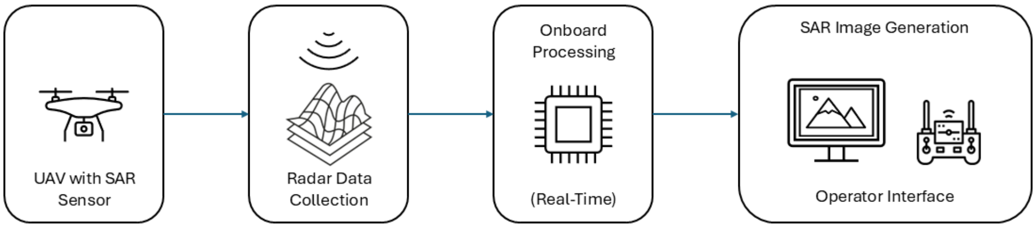

Figure 1: Conceptual Overview of Real-Time SAR Imaging with Onboard Processing

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

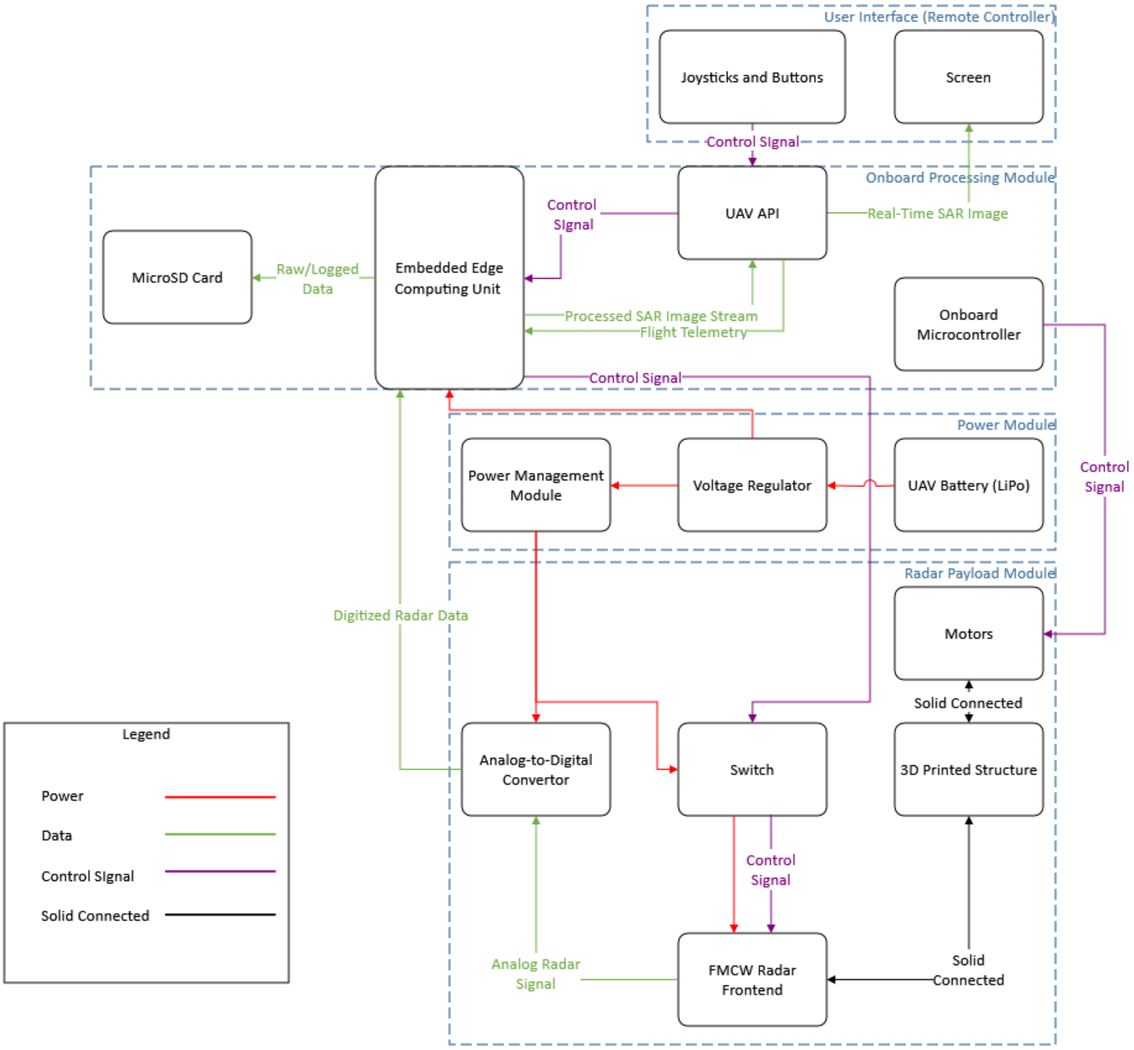

Figure 2: The Block Diagram of the Whole System

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.

Requirement	**Verification**
FMCW radar signals are generated for target sensing.	Validate transmitted signal characteristics using reference measurements.
Radar signals are transmitted toward the target area.	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]. And DJI Extension Board is employed, for easier configuration between third-party development board and the port provided by the drone. This board will be connected to the processing unit through the UART port and Network port.

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 variaty of courses and check the feedback data.
The Raspberry Pi can communicate with the drone successfully.	Connect the Raspberry Pi and the extension board. Connect the extension board to the drone. Run a simple program to acquire the position of the drone to see if the connection is successfully established.
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 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 accuracy of this subsystem is important, as errors in sampling or signal degradation will directly impact the performance of the onboard processing subsystem.

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 processing pipeline includes signal preprocessing, Fourier transform operations, and SAR image reconstruction algorithms such as the Range Migration Algorithm (RMA). Motion data from the UAV may also be incorporated to improve imaging accuracy. The processed output is a two-dimensional SAR image that represents the scanned environment.

By implementing processing onboard, the system reduces latency and allows for faster feedback compared to traditional SAR systems that rely on post-processing.

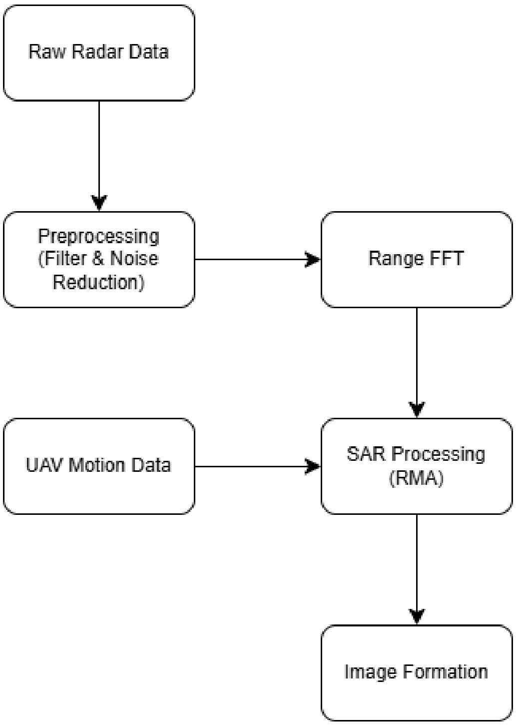

Figure 3: Onboard Processing Pipeline for Real-Time SAR Image Generation

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 that the system operates in a coordinated manner and supports real-time interaction during operation.

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

2.3 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:

$$¥50/hr \times 4 \times 120hrs = ¥24000 \simeq \$3430 \tag{1}$$

manufacturing cost:

Category	**Item Description**	**Est. Cost**
Edge Computing Platform	NVIDIA Jetson Orin Nano Developer Kit (8GB)	2500
	NVMe M.2 SSD	300
PCB & Electronics	Custom PCB Fabrication	200
	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		3850

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

[1] J. Svedin, A. Bernland, A. Gustafsson, E. Claar, and J. Luong, “Small UAV-based SAR system using low-cost radar, position, and attitude sensors with onboard imaging capability,” *International Journal of Microwave and Wireless Technologies*, vol. 13, no. 6, pp. 602–613, Mar. 2021.

[2] D. G. Gaviria, B. Geiger, C. Muth, and L. Schmalen, “On the sensing performance of fmcw-based integrated sensing and communications with arbitrary constellations,” Mar. 2025, arXiv:2503.17215. Accessed: 2026-04-06. [Online]. Available: https://arxiv.org/pdf/2503.17215

[3] DJI, *Matrice 300 RTK User Manual*, DJI, May 2023, version 4.0. Accessed: 2026-04-07. [Online]. Available: https://dl.djicdn.com/downloads/matrice-300/20230518UM/M300_RTK_User_Manual_EN_v4.0.pdf

[4] NASA Earthdata, “Synthetic Aperture Radar (SAR),” NASA, May 2021, accessed: 2026-04-07. [Online]. Available: https://www.earthdata.nasa.gov/learn/earth-observation-data-basics/sar

[5] NVIDIA Corporation, *Jetson Orin Nano Series Modules Data Sheet*, NVIDIA Corporation, Mar. 2026, version 1.7, DS-11105-001. Accessed: 2026-04-08. [Online]. Available: https://developer.nvidia.com/embedded/downloads