

# Low-Cost UAV-Mounted FMCW SAR Ground-Penetrating Radar for Landmine Detection

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# 1 Introduction

## 1.1 Problem

Armed conflict in densely populated areas result in widespread landmine and UXO (unexploded ordnance) contamination; In the Russo-Ukrainian war both anti-tank and personnel mines have been deployed in urban areas, posing risks to civilian safety.

Current demining efforts often involve handheld detection with manual instruments but are time-consuming and have inherent risk to human operators. There is ongoing research in other methods to detect and neutralize UXO and landmines more efficiently and safely, one of which is drone based remote-sensing using ground penetrating radar (GPR). When mounted to drones, these GPR drone systems can rapidly scan large areas, access terrain difficult for humans to access, and be safely operated remotely.

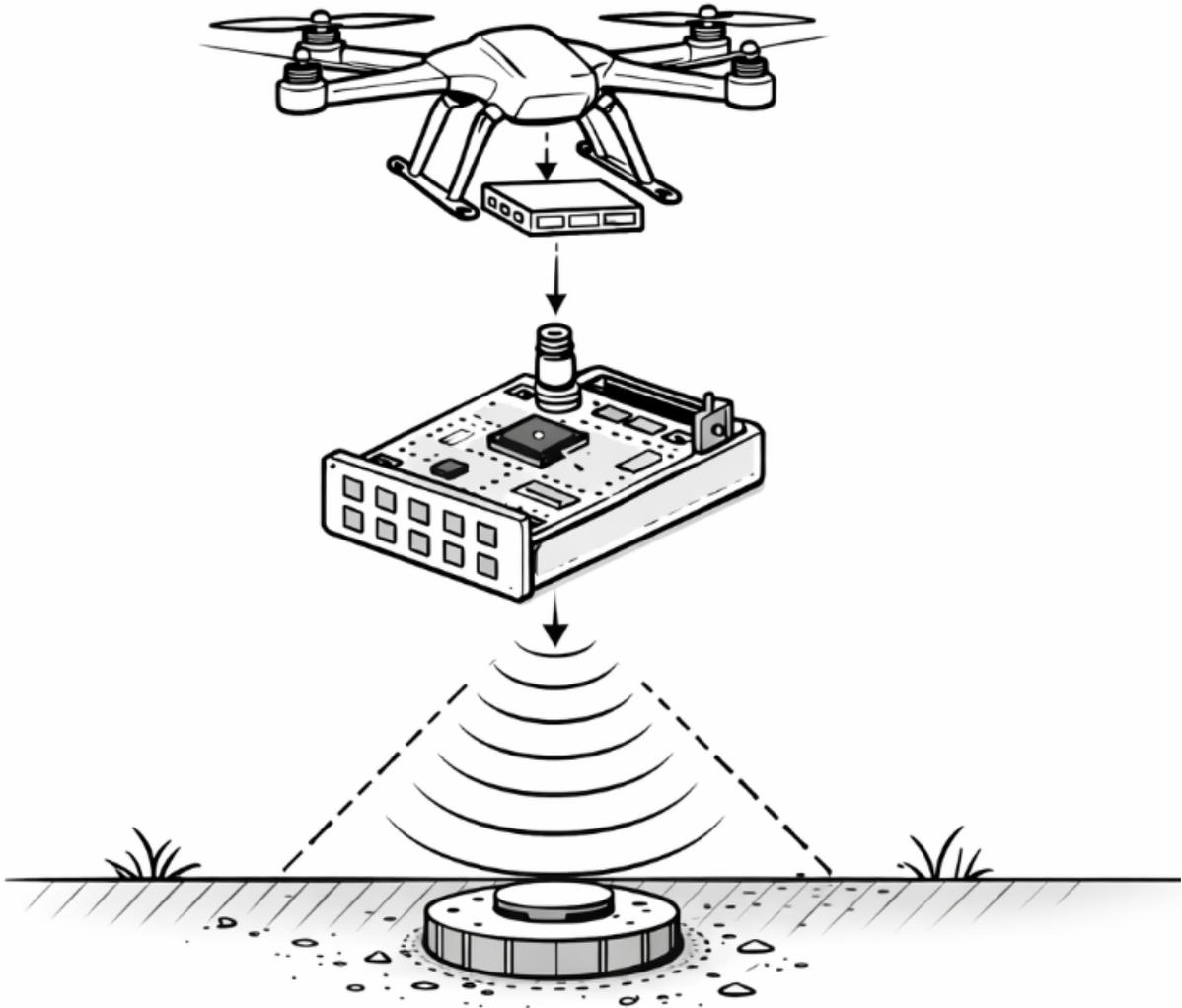
While ground penetrating radar systems for landmine detection are already commercially available, they rely on specialized and expensive electronics, making them cost-prohibitive for wide-spread deployment. In active warzones such as Ukraine, drones are regularly shot down, limiting repeated high-cost deployments. Developing low-cost, modular sensors on expendable platforms is necessary for scalable landmine detection.

## 1.2 Solution & Visual Aid

Our project is a low-cost, semi-automated, drone-mounted landmine detector using ground-penetrating radar (GPR). It leverages an inexpensive, commercially available radar chip originally designed for simple presence detection in domestic applications. This system utilizes a K-band microwave sensor module implementing Frequency-Modulated Continuous Wave (FMCW) operation, capable of detecting shallow high-reflectivity objects.

### High-Level Requirements

- Generate a **B-scan** radar image of **4 m**
- **15 cm radius** localization accuracy for a **10 cm aluminum disk** buried **5 cm** deep, at **2 m** height, within **15 seconds**.
- Implement **drone straight-line trajectory path planning**
- Live visualization on ground station of buried object locations.



## 2 System Overview

### 2.1 Block Diagram and Description

Our design consists of 3 main subsystems: Radar, Ground System, and Drone. The drone is a typical off-the-shelf drone design. It will have its own battery, flight controller, RC controller receiver, and motor controllers. We will add a PCB circuit to the drone which will take power from the drone's system, regulate it, and direct it to the MCU and radar system. The MCU will be linked to the flight controller on the drone to provide direct automated control over flight. The MCU will be wired onto the radar, and it will receive unprocessed data. The PCB will also have a WiFi transceiver which will transmit the radar data to the ground system. The WiFi chip will also receive data from the ground system telling it exactly how to control the drone. The ground system will then be able to remotely control the flight of the drone autonomously while receiving radar data. The ground system will process the radar data, organize it into intuitive visuals that show where mines might be, and map out the landscape.

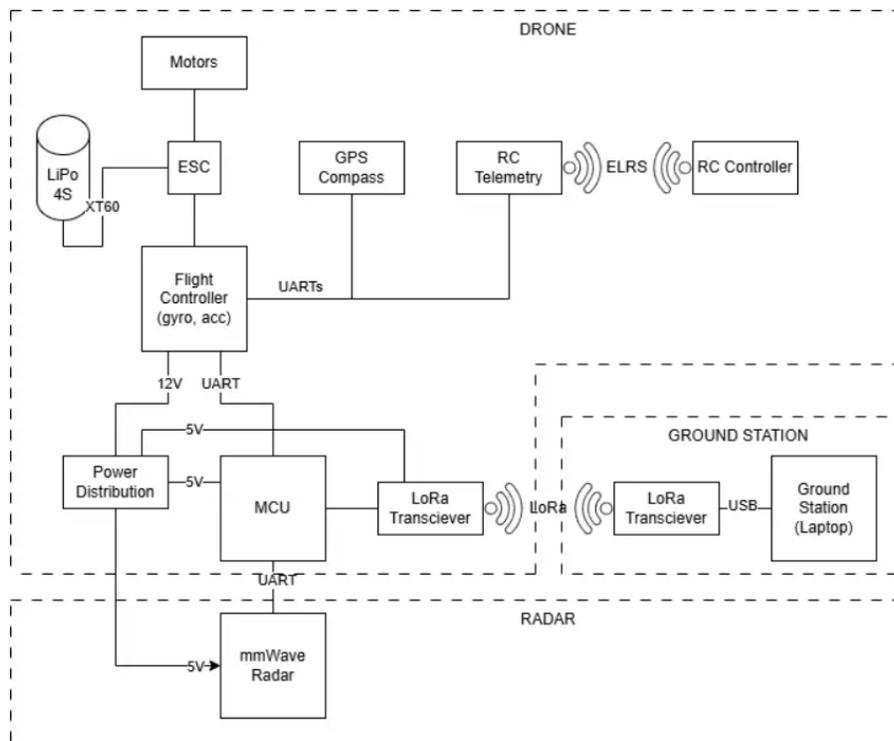


Figure 1: Low-cost UAV-mounted GPR system overview

## 2.2 Physical Design and Description

The power distribution is mounted into the drone. The drone communicates data to the Ground Station through the Lora USB transceiver, and also communicates wirelessly with the RC controller. The drone is equipped with gyro and flight controller for localization and a power distribution module that reroutes power from the drone to the radar and telemetry modules.

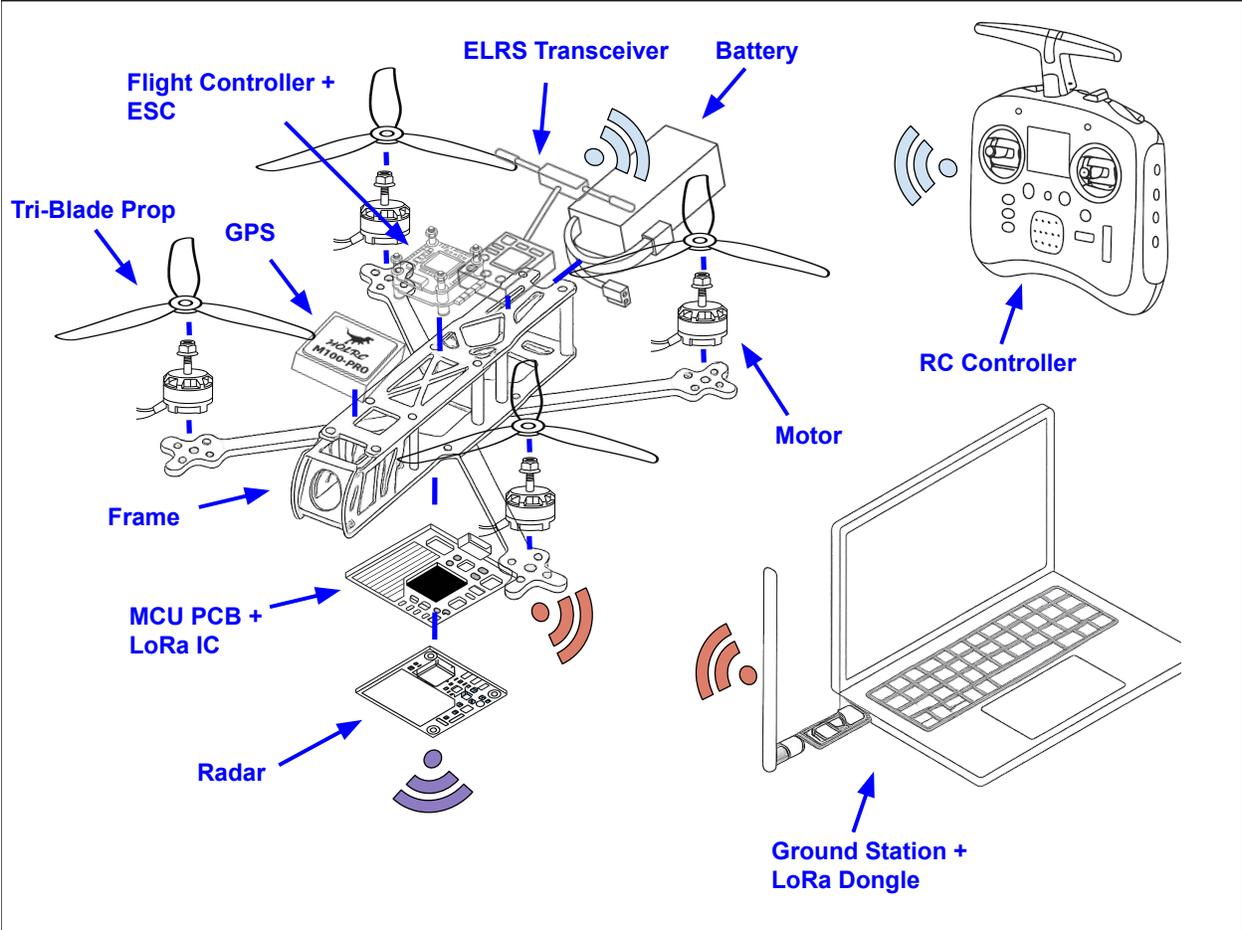


Figure 2: Low-cost UAV-mounted GPR system physical design

## 3 Subsystem 1: Radar

### 3.1 Overview



The design for the radar subsystem is modeled after the wall-penetrating radar implementation in “*Through-Wall Imaging Using Low-Cost Frequency-Modulated Continuous Wave Radar Sensors*” [4].

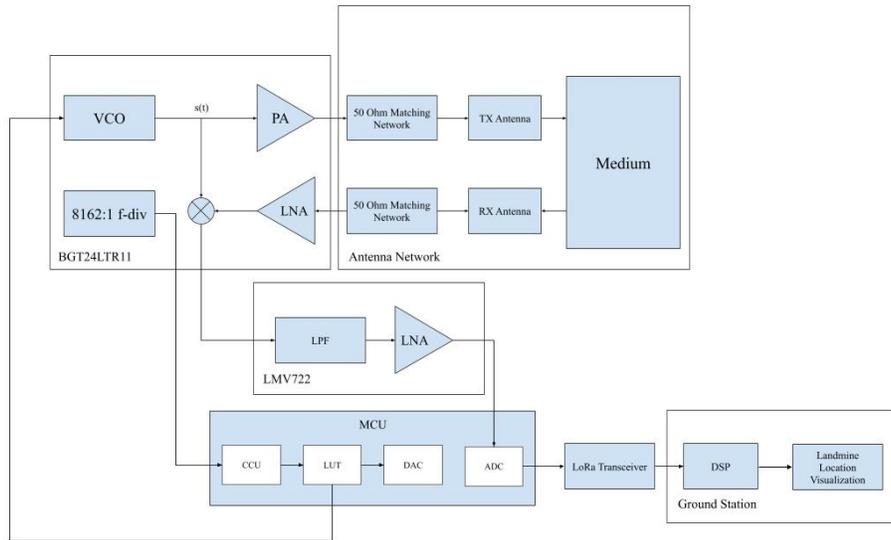


Figure 3: Low-cost UAV-mounted GPR system overview.

#### 3.1.1 Control Unit (MCU) ESP22

The control unit generates a voltage ramp for the BGT24LTR11, producing a linearly frequency-modulated (LFM) signal. It operates in an open-loop configuration with the radar system and maintains a reference table that maps the VCO input voltages of the BGT24LTR11 to their corresponding output frequencies. The unit includes a CCU used to measure the output frequency of the BGT24LTR11 during LUT creation, as well as a DAC for generating the VCO input voltages.

### 3.1.2 Antenna Network

Interfaces the BGT24LTR11 transmitter and receiver ports with their respective antennas, providing a  $50, \Omega$  impedance match. TX/RX antennas are identical patch array antennas.

### 3.1.3 BGT24LTR11

Performs FMCW radar using the MCU-generated linear voltage ramp as input. The transmitted signal is mixed with the received signal, producing an intermediate signal for processing by the DSP algorithm.

### 3.1.4 LMV722

The FMCW radar output contains a beat signal composed of a low-frequency cosine term corresponding to the target range and a higher-frequency FM component related to the carrier. By applying a low-pass filter, the high-frequency component is removed, leaving only the low-frequency beat signal, which is used for further processing.

## 3.2 Requirements

### 3.2.1 Control Unit (MCU)

- (1) Generate a voltage ramp to linearly sweep the VCO frequency from 24GHz to 24.125GHz.
- (2) Acquire 800 radar samples per scan for processing
- (3) Utilize a high-resolution 12–16 bit DAC with low differential non-linearity (DNL) for precise voltage ramp generation.
- (4) CCU to measure VCO output frequency (2.9–3.1MHz) with  $\pm 0.01$ MHz accuracy for LUT creation.
- (5) switch between LUT generation mode and measurement mode as needed.

### 3.2.2 Antenna Network

- (1) Operate over the target K-band TX/RX range
- (2) present a  $50\Omega$  interface.
- (3) transmit at minimum 50mW power.

### 3.2.3 BGT24LTR11

- (1) Operate from a 5V supply
- (2) Operate within the K-Band frequency range (24–24.25GHz)
- (3) Support a frequency sweep of at least 0.1GHz
- (4) Output power sufficient for radar detection (e.g.,  $\geq 50mW$ )
- (5) Maintain constant VCO performance over temperature variations of 25-40C.

### 3.2.4 LMV722

(1) Bandpass filter with 50dB amplification and -25dB outband attenuation. (2) Low frequency filter with upper cutoff around 10kHz.

## 3.3 Tolerance Analysis

The main tolerance analysis is in the design of the filter. According to FMCW theory, the intermediate tone consists two signals: (1) a cosine beat with frequency  $\gamma t_d$  where  $\gamma = B/T$  (sweep bandwidth/chirp duration) and  $t_d$  is the time delay from the target given by  $t_d = d/c$ , and (2) an FM term centered at  $2f_c$  where  $f_c = 24GHz$ . The beat is lower frequency than the cosine beat, but the bandwidth of the FM signal depends on the duration of the FMCW chirp. The filter must be chosen to completely filter out the higher frequency FM signal.

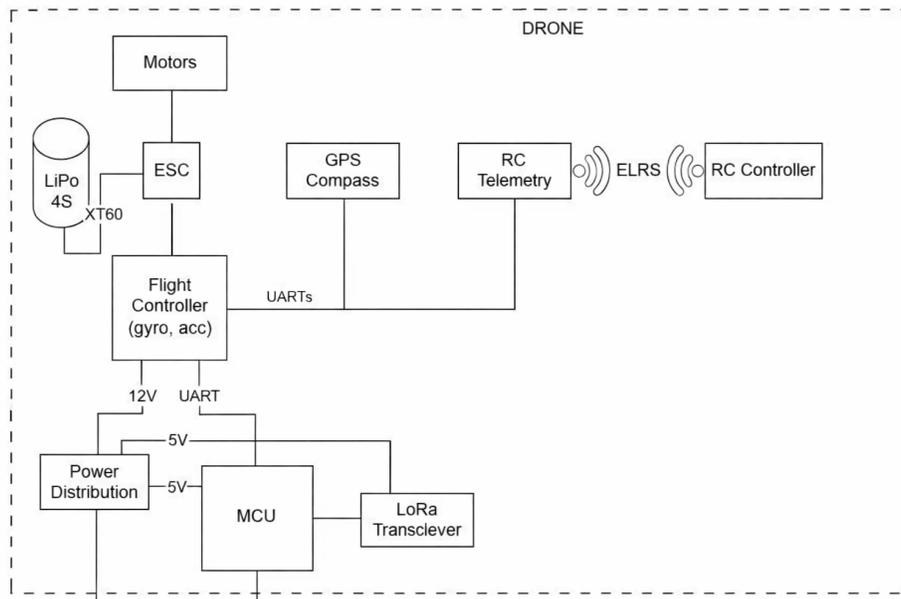
## 3.4 RV Table

Table 1: Subsystem 1 (Radar) requirements and verification plan

Req. ID	Requirement	Verification Equipment	Verification Procedure	Pass Criteria
R1-RAD	Generate linear sweep from 24.000–24.125 GHz.	Spectrum analyzer, oscilloscope	Measure frequency vs. time across sweep.	Endpoints within range and monotonic ramp.
R2-RAD	Acquire 800 radar samples per scan.	Logic analyzer, firmware logs	Trigger scan and verify buffer length.	Exactly 800 samples recorded.
R3-RAD	DAC resolution 12–16 bits.	Datasheet, oscilloscope	Verify resolution and inspect ramp smoothness.	Resolution within spec; no missing codes.
R4-RAD	Measure VCO frequency 2.9–3.1 MHz with $\pm 0.01$ MHz accuracy.	Frequency counter	Compare CCU reading to reference instrument.	Error $\leq 0.01$ MHz.
R5-RAD	50 $\Omega$ antenna interface.	VNA	Measure S11 across band.	Acceptable impedance match across band.
R6-RAD	Transmit power $\geq 50$ mW.	Power meter	Measure TX output power.	Power $\geq 50$ mW.
R7-RAD	Operate at 5 V and support $\geq 0.1$ GHz sweep bandwidth.	Bench supply, spectrum analyzer	Power at 5 V and verify sweep span.	Stable at 5 V; bandwidth requirement met.
R8-RAD	50 dB gain, $\leq -25$ dB out-of-band attenuation.	Function generator, oscilloscope	Sweep input and measure gain curve.	Gain and attenuation meet specs.

## 4 Subsystem 2: Drone

### 4.1 Overview



The drone subsystem is composed of three primary elements: the aerial platform (drone), the sensing payload (radar), and a custom-design embedded printed circuit board (PCB). This design subsystem focuses exclusively on the embedded PCB, which serves as the central integration and control module that connects the ground system, the drone, and the radar. The PCB manages power regulation and distribution from the drone, data communication to and from the ground system via a Wi-Fi chip, driving radar data acquisition, and drone flight control.

### 4.2 Requirements

#### 4.2.1 Power Regulation and Distribution

The PCB needs to take in power from the drone system. It will receive power from the 12V source in the flight controller. The flight controller has already regulated the battery power to 12V and the PCB will use a buck to regulate and drop the voltage again. The regulation ensures there is no overcurrent or excess power consumption in any components it directs power to. It must also account for any differences in operating voltage for different chips while maintaining a common ground. This means not only accounting for the typical power use of the digital IC chips, but also accounting for the inconsistent power usage of the Wi-Fi transceivers and radar module.

### **4.2.2 Data Communication**

The PCB needs to be able to collect data received from the Wi-Fi chip and drive it to send new data at rates necessary to keep up with the data acquisition of the radar. It also may need to process the radar data before sending it out. The flight instructions received from the Wi-Fi transceiver will be condensed and encrypted to save computing power and add security. The signals must also be sent fast enough to ensure safe flight of the drone with reasonable latency.

### **4.2.3 Radar Driving**

The PCB needs to drive the radar detection. This means signal generation/processing at high speeds and variable power levels. It must be able to transmit data produced by the radar in a timely and intelligent manner. It must also ensure that the radar is properly shielded from any interference that may come from the drone. This means both physical and electrical interference. Physical interference can be accounted for by wiring the radar through soft wires that allow some mechanical mount to absorb any shock or vibrations from the motors. Electrical interference can be accounted for by providing a ground plane as well as a shielding layer to prevent any signals that may be produced by the high alternating currents going through the motors from being picked up by the radar.

## **4.3 Tolerance Analysis**

We will conduct 3 tests to verify the efficacy of the design and general success of this sub-module. The first test is a test of power. This means that each component on and connected to the PCB has the appropriate power necessary for basic function. This also means that significant power can be transferred for extended periods of time without dipping below operating power for any component. The second test is a test of the transceiver. This will be a test verifying that Wi-Fi chip is capable of transmitting and receiving data at full speeds from a distance for an extended period of time. The third test will be of the radar interface which will verify typical operation of the radar including powering and collection of data at typical acquisition speeds. This data must be uncorrupted and in a usable format that can feasibly be transmitted to the ground system via the W-Fi chip. If all of these tests are passed, this is fundamental proof of hardware success and enables us to move on to software and further refinement to optimize performance.

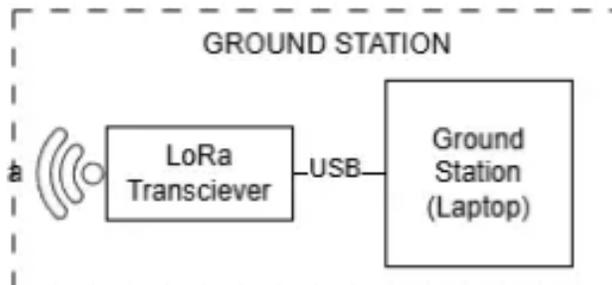
## 4.4 RV Table

Table 2: Subsystem 2 (Drone PCB) requirements and verification plan

Req. ID	Requirement	Verification Equipment	Verification Procedure	Pass Criteria
R1-PCB	Provide regulated voltage rails without brownout.	Bench supply, DMM, oscilloscope	Apply min/nom/max input and measure output rails.	Voltages within $\pm 5\%$ .
R2-PCB	Limit overcurrent and prevent excessive draw.	Bench supply	Increase load and observe current limiting.	Current remains within limit.
R3-PCB	Sustain $\geq 17$ Mbps throughput with $\leq 0.1\%$ packet loss.	Laptop, throughput tool	Run sustained data stream and log metrics.	Throughput and loss meet spec.
R4-PCB	Maintain round-trip latency $< 50$ ms.	Ping script, logging	Measure RTT during active streaming.	Max latency $< 50$ ms.
R5-PCB	Transmit radar data without corruption.	Logic analyzer, checksum validation	Verify data integrity at receiver.	Error rate below threshold.
R6-PCB	EMI from motors shall not disrupt radar operation.	Oscilloscope/FFT	Compare noise motors-off vs motors-on.	Noise increase within acceptable limit.

## 5 Subsystem 3: Ground Station

### 5.1 Overview



The Ground Station functions as the central command, processing, and visualization subsystem of the UAV-mounted FMCW ground-penetrating radar system. It consists of a laptop-class computer running custom Python software and interfaced to the drone’s MCU through a dedicated USB Wi-Fi transceiver operating on a secured local wireless network. All high-level control authority resides at the Ground Station. It can initiate or terminate autonomous flight, override onboard automation, and return control to the manual RC controller when required for safety.

This subsystem receives all telemetry data from the drone, including gyroscope, accelerometer, magnetometer, GPS, compass, and barometric measurements. These signals are used to reconstruct the drone’s trajectory and validate straight-line path planning necessary for proper B-scan radar imaging. In addition to telemetry, the Ground Station receives raw FMCW radar data from the airborne radar module. It performs all computationally intensive signal processing operations, including range FFT processing, clutter removal, envelope detection, spatial alignment, and B-scan image formation.

The Ground Station generates an intuitive 2D intensity map of subsurface reflectivity over a 4 m<sup>2</sup> scan region and highlights potential mine locations. By offloading processing to the Ground Station rather than the airborne hardware, the system reduces onboard computational requirements and enables use of lower-cost, expendable UAV platforms.

### 5.2 Requirements

The Ground Station must maintain reliable bidirectional wireless communication with the drone MCU. It must support simultaneous transmission of flight commands and reception of radar and telemetry data without data loss or unacceptable latency. The minimum sustained communication throughput shall be 5 Mbps, with support for aggregate data rates up to approximately 17 Mbps including protocol overhead. Round-trip communication latency must remain below 50 ms to ensure stable flight automation and safe operator override capability. Packet loss must remain below 0.1% to prevent radar image corruption and telemetry degradation.

The subsystem must receive telemetry data at a minimum rate of 50 Hz to accurately reconstruct drone motion and maintain spatial coherence of radar returns. GPS-derived positional drift over a 4 m<sup>2</sup> scan shall not exceed 10 cm relative error. Orientation resolution from IMU measurements shall remain within 2° to preserve radar localization accuracy.

The Ground Station must receive raw radar data at rates up to 2 MB/s and process it in real time. It shall generate a complete 2m B-scan image within 15 seconds while meeting the high-level requirement of 10 cm radius localization accuracy for a 10 cm diameter aluminum disk buried 5 cm deep at a 2 m flight altitude. The visualization interface shall refresh at a minimum rate of 10 frames per second and provide clear operator controls for scan initiation, flight mode switching, and data logging.

### 5.3 Tolerance Analysis

Communication tolerance is evaluated by comparing required data throughput to available wireless bandwidth. Radar streaming at approximately 2 MB/s combined with telemetry and command traffic results in an estimated total data requirement of approximately 17 Mbps. Using an 802.11n Wi-Fi link with typical real-world throughput of approximately 50 Mbps, system utilization remains near 34%, providing a bandwidth margin greater than 60%. This margin allows for retransmissions, interference, and moderate signal degradation while maintaining required performance. Maximum allowable round-trip latency is 50 ms; typical Wi-Fi latency of 5–20 ms combined with processing delays of approximately 20 ms yields worst-case total latency near 40 ms, preserving an approximate 20% timing margin.

Processing tolerance is evaluated based on scan timing requirements. A 4 m<sup>2</sup> scan sampled at 0.1 m resolution results in  $40 \times 40 = 1600$  spatial points. To complete imaging within 15 seconds, the processing time per point must not exceed approximately 9.4 ms. Typical laptop FFT execution times are on the order of 1 ms per transform, leaving substantial computational margin for filtering and visualization.

Localization tolerance is assessed through cumulative positional error sources. Considering relative GPS drift of  $\pm 10$  cm, IMU orientation contribution equivalent to  $\pm 5$  cm, radar range resolution of  $\pm 5$  cm, and processing uncertainty of  $\pm 3$  cm, the root-sum-square combined error is approximately 12.6 cm. This remains within the 15 cm localization requirement, providing measurable design margin.

Overall, the Ground Station satisfies throughput, latency, processing, and localization tolerances required for proof-of-concept validation while maintaining sufficient performance margin for reliable operation.

## 5.4 RV Table

Table 3: Subsystem 3 (Ground Station) requirements and verification plan

Req. ID	Requirement	Verification Equipment	Verification Procedure	Pass Criteria
R1-GS	Sustained throughput $\geq 5$ Mbps.	Laptop, throughput tool	Run bandwidth test.	Throughput meets spec.
R2-GS	Round-trip latency $< 50$ ms.	Ping script	Measure RTT under load.	Latency below threshold.
R3-GS	Packet loss $< 0.1\%$ .	Packet logging	Stream data and compute loss rate.	Loss within limit.
R4-GS	Telemetry rate $\geq 50$ Hz.	Logging software	Measure telemetry frequency.	Rate meets spec.
R5-GS	GPS drift $\leq 10$ cm over $4 \text{ m}^2$ .	Ground truth markers	Compare path to known reference.	Drift within tolerance.
R6-GS	Orientation resolution within $2^\circ$ .	IMU logs	Compare to known orientation.	Error $\leq 2^\circ$ .
R7-GS	Receive and process 2 MB/s radar data in real time.	System monitor	Stream data and monitor processing lag.	No buffer overflow or delay.
R8-GS	Generate $4 \text{ m}^2$ image within 15 s and 15 cm localization accuracy.	Test target	Run scan and measure error/time.	Time and accuracy within spec.
R9-GS	Visualization refresh $\geq 10$ FPS.	FPS counter	Measure frame rate.	FPS meets spec.

## 6 Cost and Schedule

### 6.1 Cost Analysis

A thorough cost breakdown prior to initiating design and procurement activities is essential for maintaining technical feasibility and proper scope control. Budgetary constraints directly influence system architecture, component selection, performance tradeoffs, and integration complexity, and have already affected our selection of the drone platform and radar subsystem, shaping achievable performance specifications and system capabilities. In industry, engineering labor constitutes a substantial portion of total project cost and must be included in financial planning; although team labor in senior design is not monetarily compensated and is excluded from the direct budget, it remains a finite resource. The project operates under a fixed \$150 parts budget allocated by the senior design course, which must cover required components and materials. Certain components are already accessible through existing inventory and laboratory resources, while any additional required parts may be personally procured if necessary. Fabrication and manufacturing of the custom PCB are supported by the course infrastructure and are covered independent of cost, reinforcing the need for disciplined cost management and informed technical decision-making throughout the design and implementation process.

#### 6.1.1 Labor Cost

Weekly labor cost can be estimated using the following formula:

$$\text{Labor Cost} = (\$/\text{hour}) \times 2.5 \times \text{Hours to Complete}$$

According to the 2023–2024 Illini Success report, the reported median starting salary for electrical engineering graduates is \$84,250. Based on a standard 40-hour workweek and 52 working weeks per year (2,080 total working hours annually), this corresponds to an equivalent hourly rate of approximately **\$40.50 per hour**.

We also assume that each team member is averaging a total of **10 hours** of work, including research, documentation, and testing, for a length of **10 weeks**.

Table 4: Labor Cost Breakdown by Week and Entire Project

Team Member	Hourly Rate (\$/hr)	Hours	Overhead (2.5)	Total Labor Cost (\$)
Anna Sako	40.50	10	2.5	1,012.50
Elijah Sutton	45.99	12	2.5	1,333.71
James Tang	40.50	10	2.5	1,012.50
<b>Total Weekly Labor Cost</b>				<b>3,358.71</b>
<b>Total Project Labor Cost</b>				<b>33,587.10</b>

### 6.1.2 Parts Cost

Table 5: Parts list including description, manufacturer/part number, quantity, and cost

Item	Description	Manufacturer / Part #	Qty	Unit Cost (\$)	Total Cost (\$)
1	Motors	AKK RS2205 2300kV	1	33.99	33.99
2	Frame	TBS Source One 5in	1	41.40	41.40
3	Props	iFlight 5140 5in Tri-Blade Props	1	8.99	8.99
4	ESC	QWinOut 2-4S 30A ESC	1	37.98	37.98
5	Battery	OVONIC 4S LiPo 100C 1550mAh 14.8V XT60	1	17.99	17.99
6	Charger	G.T.Power LiPo Battery Charger	1	38.99	38.99
7	ELRS Controller	RadioMaster Mode 2 ELRS	1	54.99	54.99
8	ELRS Transceiver	SpeedyBee Nano 2.4G/915MHz	1	13.71	13.71
9	GPS	HGLRC M100-5883 Pro GPS	1	23.63	23.63
10	Flight Controller + ESC	F722 Betaflight FC + 60A ESC (3-6S)	1	59.73	59.73
11	Radar	TI mmWave AWR6843ISK	1	210.01	210.01
12	LoRa Dongle	USB to LoRa Dongle	1	26.52	26.52
<b>Grand Total (Parts)</b>					<b>568.93</b>

## 6.2 Schedule

Table 6: Project timeline (by week) and division of responsibilities

Week(s)	Task / Milestone	Team Member(s) Actions
1–5	Project/Team Commencement, Project Proposal and Team Contract Submission	Group forms after each member agrees to join; each team member researches the agreed topic and prepares the proposal; team contract created and submitted.
6	Design Document Submission	Each team member continues research on their assigned subsystem and the design document is finalized.
7	2nd PCB Design Done; Purchase components (BOM finalization and ordering); Research/Design	Anna – ensure proper documentation. James – mmWave interface/software and ground penetration research/design. Elijah – drone design and hardware ordering; MCU PCB Design 2; schematic drawings.
8	3rd PCB Design Done	Anna – ground station development; ensure proper documentation. James – mmWave interface/software and ground penetration research/design. Elijah – drone assembly; MCU PCB Design 3; verification firmware.
9	Spring Break	
10	4th PCB Design Done	Anna – ground station development; ensure proper documentation. James – mmWave processing and ground penetration hardware acquisition. Elijah – drone software; MCU PCB Design 4; general integration firmware.
11	Individual Progress Reports	Anna – ground station development; demo/presentation design; ensure proper documentation. James – mmWave interface/software and ground penetration testing. Elijah – drone software and general integration software.

Table 7: Project timeline (by week) and division of responsibilities

Week(s)	Task / Milestone	Team Member(s) Actions
12	Team Contract Assessment	Anna – ground station development; team contract assessment; ensure proper documentation. James – mmWave/ground station GUI; ground penetration testing/software. Elijah – drone automation software; general integration software; ground station GUI.
13	Working Prototype	Anna – ground station finalization; ensure proper documentation; demo design. James – radar finalization; software finalization. Elijah – drone finalization; general integration finalization.
14–16	Mock Demo/Mock Presentation → Final Demo/Final Presentation	Anna – ground station finalization; ensure proper documentation; demo management; final paper writeup/delegation. James – radar finalization; software finalization. Elijah – drone finalization; general integration finalization.

## 7 Additional Considerations

In addition to the technical challenges of developing a drone-mounted radar mine detector, we must also consider broader social and human-centered factors to ensure a thoughtful and responsible design. These considerations may directly influence our technical decisions, which motivates us to develop a comprehensive and proactive assessment of potential impacts and constraints.

### 7.1 Ethics

The proposed use case of this project raises ethical considerations, as it is intended to support one nation in an active armed conflict. To maintain the most ethically responsible position possible, we frame the design objective around reducing civilian harm, particularly in Ukraine, where the conflict is physically taking place. However, despite these intentions, we acknowledge that we cannot fully control or guarantee how the system may ultimately

be used once deployed.

## 7.2 Safety

The primary safety concern is ensuring that the system performs its intended function reliably. False positives could unnecessarily prevent civilians from safely returning to their homes, while false negatives could result in serious injury or loss of life.

### 7.2.1 Cybersecurity

Because this system relies on wireless communication to transmit radar data between the drone and a ground station, cybersecurity presents significant potential risks that must be addressed as part of overall system safety. Unauthorized access to the Wi-Fi network could allow an attacker to intercept, manipulate, or inject false data, potentially producing misleading detection results with serious real-world consequences. A malicious actor could also attempt command spoofing, denial-of-service attacks, firmware tampering, or exploitation of unsecured debug interfaces to disrupt operation or repurpose the drone for unintended use. In high-stakes environments, even data interception alone may compromise mission integrity or civilian safety.

These issues are outside of the scope for our proof of concept but should be considered when expanding the project further. Such design requirements should include safeguards such as encrypted communication, mutual authentication, secure boot mechanisms, and restricted firmware access integrated into the system architecture from the outset.

## 7.3 Societal Impacts

This project carries societal implications because it is connected to an active armed conflict. While the system is intended to reduce civilian harm through safer landmine detection, some may perceive it as supporting one side of a war, leading to public scrutiny or personal judgment. This highlights that engineering decisions exist within broader social and political contexts. It is therefore important to clearly communicate the humanitarian intent of the design while acknowledging the complexity of public perception.

## 7.4 Standards

For our proof-of-concept radar drone, full military standards are not required, but several design principles are still important. The team should focus on reliability, basic environmental robustness, and electromagnetic compatibility to ensure the radar and Wi-Fi function properly despite drone vibration and motor noise, drawing inspiration from standards such as [MIL-STD-810](#) (environmental testing) and [MIL-STD-461](#) (electromagnetic compatibility). Secure communication and firmware practices are important to prevent misuse, while

safety measures should minimize risks from false detections or system failure. Finally, including an ethical framing that emphasizes civilian harm reduction demonstrates awareness of the broader societal context, showing engineering maturity without the need for formal MIL-SPEC compliance.

## References

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