Zhejiang University/University of Illinois Urbana-Champaign Institute

Senior Design Design Document

Mobile eVTOL Handling and Docking Platform

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1 Introduction

1.1 Problem

Electric vertical take-off and landing (eVTOL) aircraft are central to the emerging urban air mobility (UAM) ecosystem, with projected market growth to over $30 billion by 2030 [1]. As prototype fleets expand, vertiport and hangar operations require efficient ground handling: lifting aircraft from landing pads, transferring them to storage bays, and docking them at charging or maintenance stations [2]. Current practice for small quad-rotor eVTOL platforms (under 50 kg) relies on manual crew lifting or repurposed automotive equipment, neither of which is designed for the wide rotor span and delicate propulsion arms typical of multirotor configurations [4].

Manual handling introduces three key problems. First, inconsistent placement at docking stations increases turnaround time and risks misalignment with charging contacts. Second, the scissor-like geometry of rotor arms creates awkward lifting points that make damage likely during repositioning. Third, repeated manual lifting in confined hangar environments poses ergonomic risk to ground personnel [5]. A purpose-built, electrically driven ground support platform would address all three concerns.

1.2 Solution

We propose the Mobile eVTOL Handling and Docking Platform, a self-contained ground support system comprising three integrated subsystems: a Mechanical System for physical lifting and support, an Onboard Electronic Control System for actuation and sensing, and a Remote Control System for secure wireless operator input.

The platform drives beneath a parked eVTOL using a differential-drive mobile base, raises the aircraft with a mechanically self-locking lead-screw-driven scissor lift, deploys side wings to support the aircraft' s landing gear, transports it to a target station, and lowers it into place with sensor-guided alignment (utilizing ultrasonic and encoder feedback). An onboard Arduino Mega, supported by an isolated dual-battery architecture, coordinates all subsystems and enforces strict hardware and software safety interlocks. To ensure operational safety and prevent unauthorized access, the operator commands the platform wirelessly via a custom-built 2.4GHz RF remote controller equipped with automated failsafe logic and a physical Emergency Stop (E-Stop) system, completely eliminating the vulnerabilities of open smartphone applications.

1.3 High-level requirements list

Load Capacity and Lifting: The scissor lift subsystem must successfully lift and support a minimum static payload of 20 kg from a base height to a target height of 60 mm within 10 seconds, without structural failure or motor stall and prevent the eVTOL from tipping.

Wing Deployment: The deployable side wings must extend horizontally from a fully retracted width of 240 mm (merge within the frame) to a fully extended width of 360 mm, providing an even surface between the left and right wings.

Mobility and Dynamic Stability: Under a full payload of 20 kg, the propulsion subsystem must be able to move and turn the platform freely in any direction on a flat surface, while ensuring the resting eVTOL remains completely stable and does not shift its position by more than 3 mm during transit. The system must bring the platform to a complete stop within a braking distance of 5 cm after receiving a stop command.

2 Design

The design is partitioned into three top-level systems. The **Mechanical System (A)** comprises all physical structures and mechanisms that bear loads and execute motion. The **Onboard Electronic Control System (B)** contains the microcontroller, actuators, sensors, power supply, and wireless communication module mounted on the platform. The **Remote Control System (C)** provides the operator interface and wireless command transmission. The following subsections describe each subsystem's function, components, interfaces, and quantitative requirements.

2.1 Block Diagram

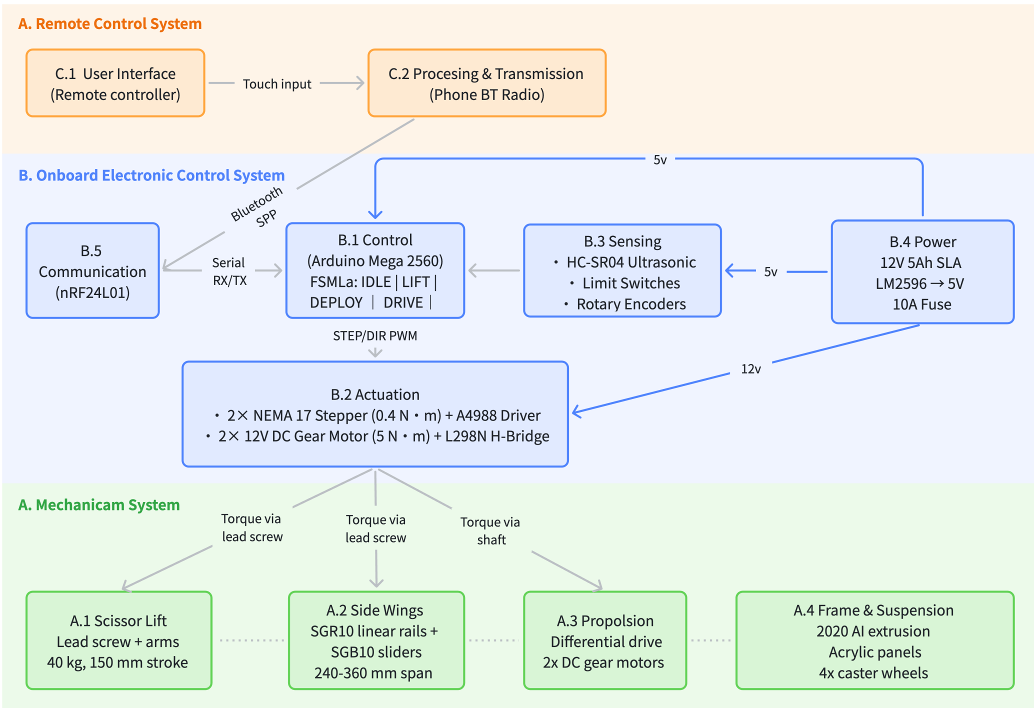


Figure 2.1: Block Diagram

2.2 Mechanical Subsystem

The Mechanical System is in charge of motions and provide structural supports. It does not contain electronic components but receives force and torque from the on-board electronic control system described in the next subsection.

2.2.1 Propulsion Components

The propulsion subsystem serves as the power source for the translation of the entire platform. It is designed for a total weight of 6 kg to provide a ~ 2.4 factor of safety for the full payload of 2.5 kg. This subsystem provides the mobility required to move and turn the platform freely in any location on a flat surface.

We selected a differential steering layout composed of two driving wheels and two unpowered caster wheels, which is essential for aligning the platform with the eVTOL. Smooth and precise differential turning ensures the resting eVTOL remains completely stable and does not shift its position by more than 3 mm during transit.

To manage large inertia, the wheels use high-damping and high-friction rubber materials. This material choice prevents the wheels from sliding to guarantee the system brings the platform to a complete stop within a braking distance of 5 cm after receiving a stop command. Mechanically, the motor shaft connects rigidly to the wheel hub using a flange coupling.

This subsystem interfaces directly with the actuation and power subsystems. The motors receive control signals from the motor driver module in the actuation subsystem. Additionally, the motors connect directly to the 12V battery in the power subsystem to receive their physical power supply.

Table 2.1: Propulsion Subsystem Component Specifications

DC Gear Motor			**Drive Wheel**		
Parameter	**Value**	**Unit**	**Parameter**	**Value**	**Unit**
Operating Voltage	12	V	Diameter	58	mm
Gear Reduction Ratio	1:72	-	Material	Rubber	-
No-load Speed	85	RPM	Rolling Resistance	0.04	-
No-load Current	$\leq$ 110	mA			
Rated Speed	64	RPM			
Rated Torque	2.6	kg·cm			
Rated Current	$\leq$ 350	mA			
Stall Torque (Max)	15.0	kg·cm			
Stall Current	1.1	A			

We verified the propulsion design using a worst-case 6 kg mass, 0.029 m wheel radius, and a rolling resistance coefficient of $\mu_r = 0.04$ (rubber on flat floor).

At the motor's rated 64 RPM (6.7 rad/s), the linear velocity is:

$$v_{max} = \omega_{rated} \cdot r \approx 0.194 \text{ m/s}$$

The continuous rolling friction F_r is:

$$F_r = \mu_r \cdot m \cdot g \approx 2.35 \text{ N}$$

This requires a steady-state torque per motor of:

$$\tau_{ss} = \frac{F_r \cdot r}{2} \approx 0.034 \text{ N} \cdot \text{m}$$

This operates safely within the motor's 0.255 N·m continuous rating. To accelerate from rest to 0.194 m/s in 0.5 s ($a = 0.388$ m/s^2), the transient torque required per motor is:

$$\tau_{peak} = \frac{(F_r + m \cdot a) \cdot r}{2} \approx 0.068 \text{ N} \cdot \text{m}$$

This peak draw easily clears the 1.47 N·m stall limit, ensuring reliable startup.

Stopping within 5 cm from v_{max} requires a minimum deceleration of 0.376 m/s^2. The natural deceleration from rolling resistance alone is:

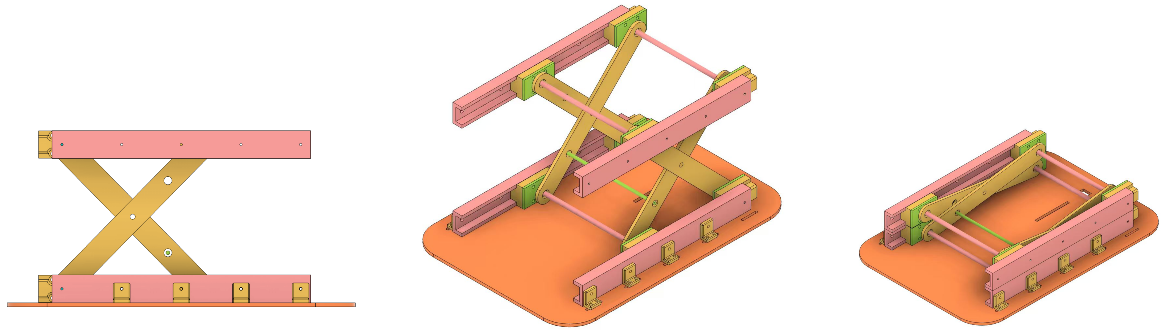
$$a_{nat} = \frac{F_r}{m} \approx 0.392 \text{ m/s}^2$$

Because $0.392 > 0.376$, the platform will coast to a complete stop in 4.8 cm simply by cutting power. Active dynamic braking via the motor driver will serve purely as redundancy and to lock the wheels in place.

Requirement	**Verification**
The platform must come to a complete stop within a braking distance of 5 cm after receiving a stop command while traveling at the maximum speed of 0.19 m/s with a 6 kg load.	Load the platform to 6 kg and operate it at maximum speed. Trigger a stop command and use a tape measure to record the distance from the trigger point to the resting position. Repeat five times to confirm the maximum distance is 5 cm or less.
The platform must ensure that a resting payload shifts by no more than 3 mm relative to the platform during both straight-line transit and differential turning.	Place a 2.5 kg payload on the platform and mark its initial position. Execute predefined straight movements and turns. Measure the payload's final displacement using digital calipers to confirm the offset does not exceed 3 mm.
The propulsion system must support a total weight of 6 kg and accelerate from rest to 0.19 m/s in 0.5 seconds or less.	Load the platform to 6 kg and initiate maximum acceleration from a stop. Monitor the velocity profile using motor encoder feedback and an oscilloscope. Record the time taken to reach 0.19 m/s to verify it is within 0.5 seconds.

2.2.2 Scissor Lift

The scissor lift architecture (see figure 2.2) is selected for its high expansion-to-compression ratio, allowing for a small minimal height, making it easy for the entire cart to enter the bottom of eVTOL. To maximize the 120N thrust provided by the linear actuators, the design uses a low-friction assembly consisting of roller carriages combined with rails and ball bearings at all joints. This allows the system to operate near its theoretical mechanical advantage. The actuator mounting point is positioned at the 1/4 position of the 203mm scissor arms to balance the lifting height and the pushing force.



(a) Side view (b) Expanded configuration (c) Compressed configuration

Figure 2.2: Mechanical layout of the scissor mechanism.

Table 2.2: Scissor Lift Subsystem Component Specifications

Mini Linear Actuator			**Scissor Mechanics**		
Parameter	**Value**	**Unit**	**Parameter**	**Value**	**Unit**
Operating Voltage	12	V	Arm Length (L)	203	mm
Max Thrust ($F_{actuator}$)	120	N	Mounting Point (x)	50.8	mm
Retracted Length	105	mm	Min Height ($\theta = 16°$)	28	mm
Extended Length	145	mm	Max Height ($\theta = 45°$)	145	mm
Stroke Speed (v_{act})	4	mm/s	Max Payload Capacity	2.5	kg

We determined the lifting capacity by analyzing the torque balance around the base hinge during the worst-case scenario. The most demanding state occurs at the minimum platform height (28 mm), where the initial starting angle is $\theta \approx 16°$.

$$\sum M = F_{actuator} \cdot d_{\perp} - W_{total} \cdot \frac{L}{2} \cdot \cos\theta = 0$$

Given the actuator's maximum thrust $F_{actuator} = 120$ N, arm length $L = 0.203$ m, and an estimated perpendicular moment arm $d_{\perp} = 0.02$ m at the lowest point:

$$W_{total} = \frac{120 \cdot 0.02}{0.1015 \cdot \cos(16°)} \approx 24.6 \text{ N}$$

This verifies that the system can safely lift a maximum payload of approximately 2.5 kg, which easily accommodates the weight of the scaled eVTOL model.

The vertical lifting speed of the platform v_y is not equal to the actuator's stroke speed $v_{act} = 4$ mm/s. Because the actuator is mounted at the 1/4 point of the scissor arm, the mechanical linkage yields a velocity multiplier of $\frac{L}{x} = 4$. We approximate the vertical velocity mapping using the geometric projection:

$$v_y = v_{act} \cdot \frac{L}{x} \cdot \sin\theta$$

At the lowest operating point ($\theta = 16°$):

$$v_{y,min} = 4 \cdot 4 \cdot \sin(16°) \approx 4.41 \text{ mm/s}$$

At the highest operating point ($\theta = 45°$):

$$v_{y,max} = 4 \cdot 4 \cdot \sin(45°) \approx 11.31 \text{ mm/s}$$

This kinematic mapping proves that the platform's vertical speed remains within a stable range, preventing any sudden inertial shifts that could tip the resting eVTOL. This allows for a fast lifting time within 15 seconds.

Requirement	**Verification**
The lift must support 2.5 ± 0.1 kg and move from a minimum height of 28 ± 2 mm to a maximum height of 145 ± 2 mm.	Place 2.5 kg of weights on the platform. Measure the height at fully retracted and fully extended states using a digital caliper to verify the range.
The lift must complete a full extension (28 mm to 145 mm) under a 2.5 kg load within 12 ± 3 seconds.	Place 2.5 kg of weights on the platform. Trigger the extension command and use a stopwatch to record the time from initial movement to the mechanical limit.

2.3 Deployable Side Wings Subsystem

This subsystem expands the platform's width from 240 mm to 360 mm using a toggle mechanism to support eVTOL landing gear. Two 140 mm linkages connect a central vertical actuator to wings sliding on 4 mm rails. The geometry reaches a mechanical dead-center at full deployment to support a 20 kg load without back-driving the lead screw.

Actuator Stroke Calculation:

The total horizontal expansion is $360 - 240 = 120$ mm, requiring each wing to translate $\Delta x = 60$ mm. With linkage length $L = 140$ mm and a horizontal final state ($x_{max} = 140$ mm, $y_{min} = 0$ mm), the retracted vertical height y_{max} is:

$$y_{max} = \sqrt{140^2 - (140 - 60)^2} = \sqrt{140^2 - 80^2} \approx 114.89 \text{ mm} \quad (2.1)$$

The linear actuator requires a minimum stroke of 115 mm.

Figure 2.3: The linkage deployment mechanism and guide rails.

Requirement	**Verification**
The total platform width must expand from 240 ± 2 mm to 360 ± 2 mm.	Fully retract the wings and measure the outer width using a digital caliper. Then fully deploy the wings and repeat the measurement to verify the expansion range.
The deployed wings must sustain a 2.5 kg static load with an edge deflection of ≤ 2.0 mm.	Apply 2.5 kg of weights to the deployed surface. Measure the vertical displacement at the wing tip using a dial indicator to verify that the edge deflection remains within the allowable limit.

2.4 Onboard Electronic Control Subsystem

The onboard electronic control system serves as the central hub of the platform, receiving wireless commands from the remote control system, reading real-time sensor feedback, and driving all actuators to perform lifting, wing deployment, and locomotion. An Arduino Mega 2560 coordinates every sensor input and actuator output through closed-loop logic that prioritizes safety at every cycle.

The power architecture uses two electrically isolated batteries: a 12 V lithium-ion pack powers all motors and linear actuators, while a separate 7.4 V pack supplies only the microcontroller and sensors. This isolation prevents voltage spikes and electromagnetic interference generated by motor switching from corrupting the control logic. On the safety side, the system incorporates both an emergency-stop switch for operator-initiated shutoff and in-line fuses for passive overcurrent protection.

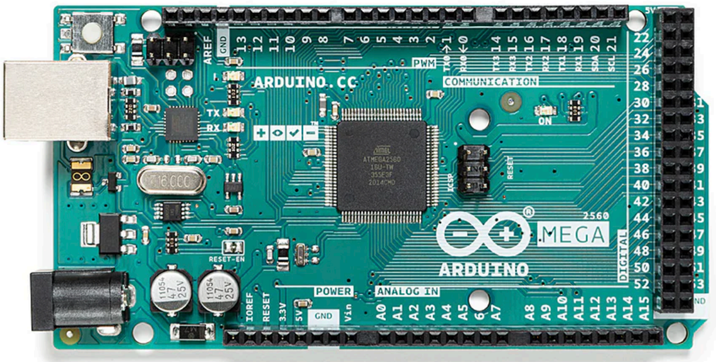


Figure 2.4: Image of Arduino Mega 2560

2.4.1 Control Subsystem

The Arduino Mega 2560 serves as the central controller. It outputs PWM signals and GPIO levels to drive the motor driver board and relay bank, communicates with the nRF24L01+ wireless module over SPI, and reads limit switches and an ultrasonic height sensor through digital and analog pins. The Mega 2560 is chosen over the UNO because the system simultaneously occupies PWM, GPIO, SPI, and analog input channels that exceed the UNO's pin count. The board is powered by the independent 7.4 V battery through its V_{in} pin; the on-board AMS1117 regulator steps this down to 5 V and 3.3 V, so no external buck converter is needed.

Each main-loop iteration follows a fixed priority: first, the controller checks the emergency-stop line and all limit switches—if any are triggered, the corresponding actuators are immediately de-energized; next, it parses any incoming wireless command from the nRF24L01+ receive buffer; finally, it reads sensor feedback and issues the appropriate motor or relay control outputs. All signal routing currently uses a breadboard and DuPont jumper wires for prototyping; a dedicated PCB will replace this in the final integration phase.

Requirement	**Verification**
The main control loop shall complete within 50 ms to ensure real-time response to commands and sensor events.	Print a timestamp via Serial at each loop entry for five continuous minutes. Confirm the average period is ≤ 50 ms and no single iteration exceeds 60 ms.
Upon receiving an emergency-stop signal, the controller shall cut all 12 V power outputs within 100 ms.	Attach oscilloscope probes to the e-stop input and the motor supply rail. Press the e-stop button and measure the time between the two edges. Repeat ten times; all readings shall be ≤ 100 ms.
The controller shall run a full operational sequence (lift, deploy wings, drive, retract) continuously for 30 minutes without freezing or resetting.	Execute an automated test script that cycles through all operations. Monitor Serial output throughout; any gap exceeding 1 s constitutes a failure.

2.4.2 Actuation Subsystem

The actuation subsystem converts low-voltage control signals from the Mega into mechanical motion. Two 12 V DC gear motors, each equipped with a built-in encoder, drive the left and right wheels through a dedicated motor driver board that accepts PWM speed and digital direction signals from the Mega. Differential control of the two wheels enables forward, reverse, and turning maneuvers.

Three 12 V miniature linear actuators drive the scissor lift and the deployable side wings. Each actuator is a self-contained unit housing a DC motor and a lead screw internally; applying voltage in one polarity extends the rod, and reversing the polarity retracts it. Two relays per actuator handle this polarity reversal, and de-energizing both relays locks the actuator in place. The two side-wing actuators are wired in parallel to a single relay pair so that they extend and retract synchronously. This yields a total of four relays: one pair for the scissor-lift actuator and one pair for the two wing actuators. All actuator power is drawn from the 12 V battery through the emergency-stop switch and fuse; the Mega supplies only the low-current relay coil signals.

Requirement	**Verification**
The scissor lift shall complete a full stroke under rated payload without stalling or jamming.	Load the platform to its rated payload. Execute ten consecutive full lift–lower cycles and confirm each completes smoothly with consistent timing (standard deviation $< 10\,\%$).
Both side-wing actuators shall complete full deployment within 25 s.	Trigger the deploy command and time the stroke with a stopwatch. Repeat five times; all readings shall be ≤ 25 s.
During differential turning, the left and right wheel speeds shall not differ by more than 5 % when given identical commands.	Command both wheels to the same target speed. Read encoder feedback and compute $\lvert V_L - V_R \rvert / V_{avg}$. All ten trials shall yield $\leq 5\,\%$.

2.4.3 Sensing Subsystem

The sensing subsystem provides the controller with real-time state feedback and, critically, prevents mechanical over-travel that could damage the structure. It comprises three sensor types: limit switches, an ultrasonic height sensor, and wheel encoders.

Limit switches are installed at the top and bottom travel limits of the scissor lift and at the fully-deployed and fully-retracted positions of the side wings. All switches use a normally-closed wiring scheme: the circuit remains closed during normal travel, and opening the circuit upon contact pulls the corresponding Mega input HIGH, which immediately de-energizes the associated actuator. The normally-closed configuration is a deliberate fail-safe—if a wire breaks or a connector loosens, the signal also goes HIGH, causing the system to halt rather than to continue driving into a mechanical stop. An HC-SR04 ultrasonic sensor is mounted on the lifting platform to provide continuous height measurement across the full stroke, enabling proportional height control rather than simple two-point switching. Rotary encoders integrated inside the drive motors supply wheel-speed and cumulative-distance feedback through the motor driver board. Additionally, a resistive voltage divider connected to one of the Mega's analog inputs monitors the 12 V battery voltage; when the reading drops below a safe threshold, the controller transmits a low-battery warning to the remote operator via nRF24L01+.

Requirement	Verification
Every limit switch shall reliably halt its associated actuator upon activation with a 100 % success rate.	Manually trigger each of the limit switches 20 times. Confirm the corresponding actuator stops on every trial (total: all triggers successful with zero misses).
The ultrasonic height sensor shall maintain ± 5 mm accuracy over the full working range.	Set ten known heights using a vernier caliper at equal intervals across the stroke. Compare each sensor reading to the caliper value; all deviations shall be ≤ 5 mm.
Encoder-reported wheel speed shall deviate no more than 3 % from the actual motor speed.	Simultaneously measure the motor speed with the encoder and an optical tachometer at steady state. Compute the relative error over ten trials; all shall be ≤ 3 %.

2.4.4 Power Subsystem

The power subsystem uses two fully isolated battery packs. A 12 V (3S 18650) lithium-ion pack serves as the traction supply for all actuators: the two drive motors draw power through the motor driver board, and the three linear actuators draw power through the relay bank. A 7.4 V (2S 18650) pack serves as the control supply, connected to the Mega's V_{in} pin; the board's on-board AMS1117 regulator produces the 5 V and 3.3 V rails for the microcontroller and all sensors. Because the regulator is already integrated on the Mega, no external buck-converter module is required.

Two complementary protection mechanisms guard the system. An emergency-stop switch—a normally-closed mushroom-head pushbutton—is wired in series with the 12 V positive rail. Pressing it physically opens the traction circuit, instantly de-energizing every motor and actuator; releasing it restores power. A fuse is placed in series on each battery output line (3 A on the 12 V line, 1 A on the 7.4 V line). In the event of a short circuit or sustained overcurrent, the fuse blows autonomously to prevent wiring damage or battery thermal runaway. The emergency-stop switch is the operator's active safeguard; the fuse is the circuit's passive last line of defense. The complete 12 V power path is: battery → emergency-stop switch → fuse (3 A) → distribution to motor driver board and relay bank.

Requirement	Verification
All actuators shall be fully de-energized within 50 ms of pressing the emergency-stop switch.	Attach oscilloscope probes to the e-stop signal and the motor supply rail. Press the e-stop and record the voltage-fall time. Repeat ten times; all shall be ≤ 50 ms.
The fuse shall blow within 1 s under a short-circuit condition.	Under controlled conditions with a current-limiting resistor, simulate a short circuit on the 12 V line. Confirm the fuse opens within 1 s.
The Mega's 5 V output shall remain within ± 5 % (4.75–5.25 V) with all sensors connected.	Connect all sensor loads and monitor the Mega's 5 V pin with a multimeter for ten minutes. Confirm the reading stays within the specified range throughout.

2.4.5 Communication Interface

The platform carries an nRF24L01+ module with an integrated PA and LNA antenna, operating in the 2.4 GHz ISM band. It connects to the Mega via the hardware SPI bus and serves as the wireless bridge between the onboard system and the remote controller. The nRF24L01+ is chosen over Bluetooth and infrared for three reasons: it does not require line-of-sight, which is essential when the platform operates underneath the eVTOL fuselage; its PA+LNA variant provides reliable communication beyond 15 m; and its lightweight packet protocol introduces less latency than Bluetooth's connection-management overhead. The detailed communication protocol and remote-side design are presented in Section C (Remote Control System).

Requirement	**Verification**
Packet loss rate shall be below 1 % at a range of 15 m with no direct line of sight.	Transmit 1 000 command frames from the remote controller at 15 m with an obstacle between the two modules. Count successful acknowledgments; the loss rate shall be < 1 %.
End-to-end command latency, from transmission to Mega parsing completion, shall not exceed 50 ms.	Timestamp each packet at the transmitter and log the parse-complete time at the receiver. Compute the difference over 100 trials; all shall be ≤ 50 ms.
The wireless link shall remain connected for 30 continuous minutes without dropout.	Transmit a heartbeat packet every 200 ms for 30 minutes. Log every received heartbeat; any gap exceeding 1 s constitutes a failure.

2.5 Remote Control Subsystem

In this project, the remote control subsystem is centered on **Arduino Mega 2560** as the onboard controller. For the wireless link, we use nRF24L01+ (PA+LNA version) operating in the 2.4 GHz ISM band, instead of smartphone-based control.

2.5.1 Wireless Module: nRF24L01+ (PA+LNA)

The remote controller transmits motion and actuation commands to the vehicle through nRF24L01+, while the vehicle returns status/acknowledgment frames.

nRF24L01+ provides hardware-level **Auto-ACK** and retransmission support. After each packet transmission, the transmitter can determine whether the receiver has acknowledged successfully. This enables a simple and robust fail-safe strategy:

- If the vehicle does not receive a valid control frame for more than $T_{\text{loss}} = 500$ ms, trigger E-Stop.
- If the remote side misses ACK for $N_{\text{fail}} = 5$ consecutive transmissions, trigger E-Stop.

Let control frame period be $T_s = 20$ ms (50 Hz), then link-loss timeout corresponds to:

$$N_{\text{timeout}} = \frac{T_{\text{loss}}}{T_s} = \frac{500}{20} = 25 \text{ frames} \tag{2.2}$$

So the platform enters safe state if 25 consecutive frame periods pass without valid packets.

nRF24L01+ operates in the **2.4 GHz ISM band**, which maps naturally to **FCC Part 15** low-power unlicensed operation requirements. This provides a clear path to address the "Regulatory Standards" item in design reviews and scoring rubrics.

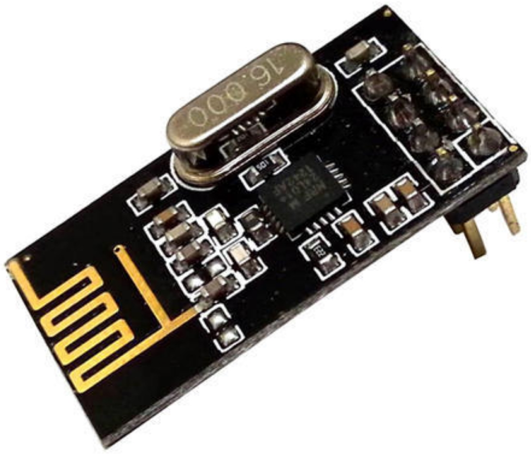


Figure 2.5: nRF24L01

nRF24L01+ supports channel configuration and multiple logical data pipes. By assigning a dedicated RF channel and unique pipe address, the system reduces the risk of:

- accidental cross-control from nearby teams' remotes,
- interference from congested channels.

A practical enhancement is software-based channel hopping among a predefined whitelist:

$$f_k = f_0 + \Delta f \cdot k, \quad k \in \{0, 1, \ldots, M - 1\} \tag{2.3}$$

where f_0 is the base channel and Δf is the hopping interval.

2.5.2 System Interface with Arduino Mega 2560

Onboard side:

- MCU: Arduino Mega 2560
- RF module: nRF24L01+ (PA+LNA), connected via SPI
- Typical SPI pins (Mega 2560): MOSI(51), MISO(50), SCK(52), CSN/CE as GPIO

The Mega 2560 parses remote commands and forwards validated control actions to motor/lift/wing actuation logic. All safety-critical actions (E-Stop, watchdog timeout, command validation) are executed on the Mega side.

2.5.3 Requirement and Verification

Table 2.3: Remote Control Subsystem Requirement and Verification (nRF24L01+ based)

Requirement	Verification
The wireless remote link shall use nRF24L01+ (PA+LNA) with Arduino Mega 2560 as onboard controller.	Inspect BOM and wiring; verify SPI communication and successful packet exchange between remote node and Mega 2560.
The system shall trigger E-Stop if no valid control packet is received for more than 500 ms.	Transmit control at 50 Hz, then power off remote transmitter; measure time from last valid packet to motor-disable signal. Pass if $\leq$ 500 ms in all 10 trials.
The system shall trigger E-Stop if ACK is missed for 5 consecutive transmissions at remote side.	Introduce controlled RF blockage; log ACK failure counter in firmware. Pass if E-Stop command is asserted at the 5th consecutive ACK miss.
The wireless link shall achieve packet success rate $\geq$ 99% in indoor LOS at 10 m.	Send 1000 sequential frames with sequence IDs; compute success ratio from received IDs and ACK logs. Pass if success ratio $\geq$ 99%.
The communication design shall satisfy unlicensed 2.4 GHz operation documentation requirement (FCC Part 15 reference).	Provide frequency band, output power class, and FCC Part 15 citation in design compliance section; review checklist signed by team.

2.6 Tolerance Analysis

The most critical part of the eVTOL Support Platform project is the reliable execution of precise mechanical movements and secure wireless control. This component integrates the propulsion braking system, the scissor lift mechanism, and the RF communication link. Failure in this subsystem would render the platform unsafe and incapable of supporting the eVTOL during transit and lifting.

(1) Design-Level Risks

- **Propulsion and Braking:** The platform must manage heavy inertia and stop strictly within a 5 cm braking distance to prevent misalignment or collision.
- **Mechanical Lifting Capacity:** The scissor lift must provide sufficient torque at its lowest mechanical advantage point to safely lift the 2.5 kg payload without actuator stall.
- **Communication Reliability:** The system must handle potential wireless interference or packet loss in the 2.4 GHz band without losing control of the heavy platform.

(2) Propulsion and Braking Calculation

For the platform traveling at a maximum velocity:

$$v_{max} = \omega_{rated} \cdot r \approx 0.194 \text{ m/s}$$

The natural deceleration provided by rolling resistance F_r for a mass m:

$$a_{nat} = \frac{F_r}{m} \approx 0.392 \text{ m/s}^2$$

Because a_{nat} (0.392 m/s^2) exceeds the required minimum deceleration (0.376 m/s^2), the platform naturally coasts to a complete stop in 4.8 cm, falling safely within the 5.0 cm tolerance.

(3) Lift Parameter Calculation

The lifting capacity is verified by the torque balance around the base hinge at the worst-case starting angle $\theta \approx 16°$:

$$\sum M = F_{actuator} \cdot d_{\perp} - W_{total} \cdot \frac{L}{2} \cdot \cos\theta = 0$$

This guarantees the mechanism can support $W_{total} \approx 24.6$ N (approx. 2.5 kg). The vertical lifting speed v_y is constrained by the linkage geometry to prevent sudden inertial shifts:

$$v_y = v_{act} \cdot \frac{L}{x} \cdot \sin\theta$$

(4) Communication Timeout Calculation

To prevent runaway scenarios, the link-loss timeout frame threshold $N_{timeout}$ is defined by the loss duration T_{loss} and the control frame period T_s:

$$N_{timeout} = \frac{T_{loss}}{T_s} = \frac{500}{20} = 25 \text{ frames}$$

The platform's design for aligned transit, lifting, and remote operation is mathematically feasible. Calculations validate that the system inherently meets the required braking distance tolerances, provides sufficient mechanical advantage for the payload, and employs rigorous timeout thresholds to ensure operational safety.

3 Cost and Schedule

3.1 Cost Analysis

Labor Cost: 0 dollar/h * 10 h/week * 10 weeks = 0

Parts:

Table 3.1: Cost Analysis

Item	**Cost (RMB)**
Two 1:90 Gear Motors	125
Motor Driver Circuit Board	50
Arduino Mega Board + Cable	220
Electric Linear Actuator (50mm, 100mm)	190
Optical Shaft (20cm, 6mm, 5 pcs)	120
Optical Shaft (30cm, 4mm, 1 pc)	20
Linear Guide Rails (30cm, 4 pcs)	160
Aluminum Plate (1 m^2, 2–4mm thick)	300
Acrylic Plate (4mm, total ~1200 cm^2)	10
8V Battery	30
Bearings (6mm inner, 10mm outer, 20 pcs)	30
M4/M5 Screws and Nuts	10
3D Printing (Estimated)	80
Miscellaneous (small components, etc.)	50
Total	**1395**

The cost estimation includes both fixed-price components and materials with approximate costs. Items such as shafts, plates, bearings are marked as estimated due to price variations depending on suppliers and specifications. The total cost will be finalized after procurement.

3.2 Schedule

Table 3.2: Project schedule with weekly task assignments.

Week	**Haowen Chen** (Mechanical)	**Shu Yang** (Mechanical)	**Ruiling Xu** (Electrical)	**Yuchen Zhang** (Electrical)
2/25	Research scissor-lift and side-wing mechanisms	Parameter calculation, component selection	Research Arduino control architecture	Research Bluetooth (HC-05) protocol
3/3	Scissor-lift and side-wing CAD modeling		Component procurement; circuit schematic design	RFA document preparation
3/10	Chassis frame and upper platform CAD	Side-wing rail assembly CAD	Breadboard stepper motor driver test	Bluetooth pairing test with smartphone
3/17	Force analysis and tolerance calculation	Stroke verification and interference check	Breadboard DC motor driver test	App Inventor remote control UI
3/24	3D-printed part design (hinge brackets, motor mounts)	Drive wheel and rail mounting bracket design	Sensor wiring (HC-SR04, limit switches)	Arduino state machine code framework
3/31	Complete full CAD assembly; Proposal & Design Doc writing		Design Doc writing (electrical sections, tolerance analysis)	
4/7	Order parts; begin 3D printing	Cut aluminum; assemble chassis frame	Design and order PCB shield	Closed-loop lift control code
4/14	Assemble scissor-lift mechanism	Assemble side-wing mechanism	Solder PCB; complete wiring	Differential drive and encoder code
4/21	Mechanical–electrical integration and joint debugging			
4/28	Full-system workflow test (lift–deploy–drive–dock)		E-stop and limit switch verification	Bluetooth full-function test
5/5	Mock Demo rehearsal; verify all R&V items and record test data			
5/12	Final Report writing (mechanical design, CAD, analysis)		Final Report writing (circuit, code, test data)	
5/19	Final Demo and presentation			

4 Ethics and Safety

4.1 Ethical Considerations

The primary ethical consideration for our Mobile eVTOL Handling and Docking Platform aligns with Canon 1 of the IEEE Code of Ethics: "to hold paramount the safety, health, and welfare of the public." Our platform is designed to transport a 40 kg eVTOL payload, bringing the total system mass to over 50 kg. This mass, combined with the mobility of the cart, poses a significant kinetic and crushing hazard if control is lost or manipulated by unauthorized personnel.

To address this ethical obligation, we deliberately avoided using a smartphone application and an open Bluetooth protocol (e.g., HC-05). Instead, we designed a custom Arduino Mega-based remote controller utilizing the nRF24L01+ 2.4GHz transceiver. By implementing specific communication pipe addresses and proprietary data packet structures, we ensure that only the paired remote can command the platform. This design decision fundamentally mitigates the risk of unauthorized access or malicious hijacking, thereby protecting bystanders and the expensive eVTOL equipment from unintended vehicle movements.

4.2 Safety and Hazard Mitigation

To ensure safe operation and regulatory compliance, our system incorporates several robust hardware and software safety mechanisms targeting specific engineering hazards:[3]

4.2.1 Communication Loss and Failsafe Logic

A critical industrial safety concern is the loss of connection between the remote and the platform. We implemented a "dead-man's switch" logic using the nRF24L01+ module's Auto-ACK (Auto-Acknowledgment) feature. If the onboard receiver fails to receive a valid command packet from the remote for more than 500 ms, the microcontroller automatically cuts power to all actuation subsystems. Because the T8 lead screw in the scissor lift and the drive motors are mechanically self-locking, cutting the power immediately freezes the platform in its current state rather than dropping the payload. In addition to this autonomous software failsafe, a physical Emergency Stop (E-stop) button is provided on the platform as a manual hardware override to instantly sever power and halt all operations regardless of the microcontroller's state. Furthermore, the 2.4GHz RF module operates strictly within the allowable transmission power limits specified by FCC Part 15 for unlicensed industrial, scientific, and medical (ISM) bands.

4.2.2 Mechanical Hazards

The scissor lift mechanism inherently creates hazardous pinch points during its expansion and contraction phases. To comply with OSHA standard 1910.212(a)(1) regarding machine guarding, physical acrylic guards will be placed around the core electronic components, and high-visibility warning labels will mark the mechanical pinch zones. Additionally, hardware limit switches are installed at the maximum and minimum extension points of the lift. These act as an absolute hardware override to instantly cut motor power, preventing structural failure even if the software control loop fails.

4.2.3 Operational Awareness

Since our dedicated remote controller does not feature a graphical user interface (GUI), we address the safety need for environmental awareness through a system of specific LED blinking patterns and an onboard buzzer. For instance, if the HC-SR04 ultrasonic sensor detects an unexpected obstacle in the docking path, the system triggers a high-frequency red LED flashing sequence. This provides immediate, unambiguous physical feedback to both the operator and nearby personnel.

4.2.4 Electrical and Fire Hazards

To mitigate the risk of electrical fires and ensure absolute control over the high-power actuators, the platform employs a dual-battery power architecture. A 12V battery is dedicated to the high-current demands of the two drive motors and three stepper motors, while a separate 9V battery independently powers the Arduino Mega logic and sensors. This isolation prevents inductive voltage spikes from the motors from causing logic resets. Crucially, a high-visibility, physical Emergency Stop (E-stop) button is integrated directly into the 12V power rail. Activating the E-stop physically severs the power to all motors. Due to the mechanical self-locking nature of our lead screw and motor gearboxes, this ”power-off” state ensures the platform maintains its current position and height without collapsing, fulfilling the safety requirements for handling sensitive eVTOL equipment. Additionally, inline fuses are installed to protect the system from short-circuit-induced thermal runaway.

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