4.8 Typical Vehicles and Extensions

Chapter Outline

Typical Unmanned Vehicle Modeling and Extensions

Chapter 4
Vehicle Motion Modeling and Simulation

4.1 Modeling Fundamentals and Kinematics
4.2 Rigid-Body Dynamics and Solvers
4.3 Propulsion, Forces, and Observations
4.4 Trim, Linearization, and Dynamics
4.5 Multicopter Modeling and Simulation
4.6 Measurement and Static Identification
4.7 Dynamic Identification and Refinement
4.8 Typical Vehicles and Extensions
4.9 Modeling Tools and Deployment
4.10 API and SDK Modeling Interfaces
4.11 Examples and Integrated Practice
4.12 Exercises and Course Projects

4 Units in This Section

4.8.1 Multicopter UAVs

Textbook: Sec. 4.2.5.1

4.8.2 Fixed-Wing UAVs

Textbook: Sec. 4.2.5.2

4.8.3 Unmanned Ground Vehicles

Textbook: Sec. 4.2.5.3

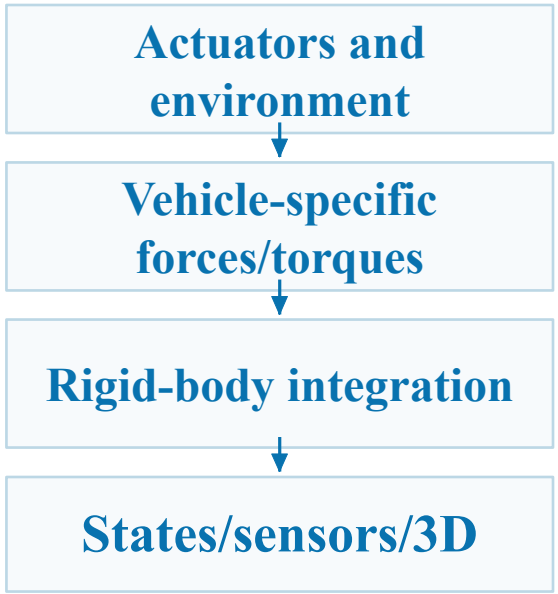
4.8.4 Other Vehicles and Model Selection

Textbook: Secs. 4.2.5.4 and 4.3.2

4.8.1 Multicopter UAVs: Force Sources Across Vehicles

Changing Vehicles Means Changing the Force Model

- Quadcopters, fixed-wing aircraft, and ground vehicles can share rigid-body integration. Rotor thrust, wing aerodynamics, and tire–ground interaction produce different resultant forces and torques.
- Match actuators, forces, mass/inertia, initial states, and environment. The 3D appearance ID (ClassID, introduced in Section 4.9) selects appearance; force modules determine dynamics.
- Trace inputs to the force modules to identify the model. Legacy names such as uav, rotor, and MotorRads are only names; calculations determine physical meaning and units.



Reusable framework and vehicle-specific force sources

Reuse the rigid-body solver; adapt forces, actuators, and constraints.

4.8.1 Multicopter UAVs: Control Channels Across Vehicles

Match Control Channels to Physical Actuators

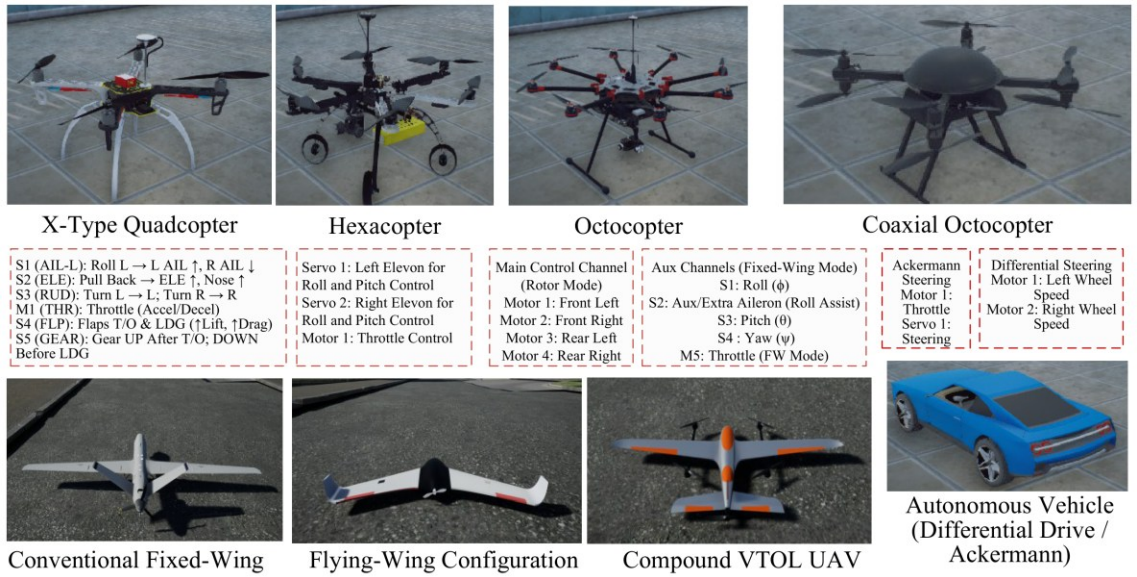


Figure 4.14 Control Channels of Different Unmanned Vehicles

- **Top row:** multicopter rotor counts and layouts; lower-row channels are enlarged next page.

Actuators and layout give a channel its physical meaning.

4.8.1 Multicopter UAVs: Channels in Figure 4.14

One Channel Number Can Drive Different Actuators

Vehicle	Channels and actuators (function)
Conventional fixed-wing	Servo 1: aileron (roll); 2: elevator (pitch); 3: rudder (yaw); 4: flap (lift augmentation); 5: landing gear. Motor 1: throttle.
Flying wing	Servos 1 and 2: left/right elevons for roll and pitch. Motor 1: throttle.
Hybrid fixed-wing	Primary (rotor mode), motors 1−4: front left/right, then rear left/right. Auxiliary (fixed-wing mode), servos 1−4: aileron, extra aileron, elevator, rudder; motor 5: throttle.
Ackermann chassis	Motor 1: throttle; servo 1: steering.
Differential-drive chassis	Motor 1: left-wheel speed; motor 2: right-wheel speed.

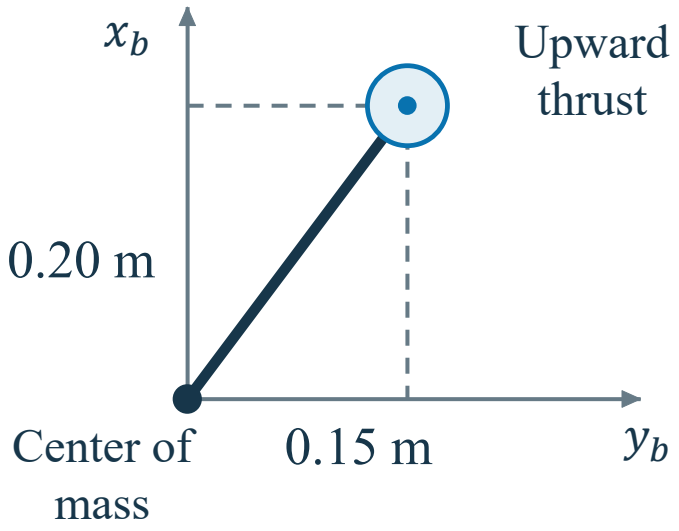
- Fixed-wing channels serve control surfaces and throttle; vehicle channels serve drive and steering.

Lower-row channel labels from Figure 4.14; numbering follows the selected example's mapping.

4.8.1 Multicopter UAVs: One Rotor's Moment Arm

Position and the Cross Product Determine Rotor Torque

- Use the center of mass as the forward-right-down (FRD) body-frame origin. Rotor position: $[0.20, 0.15, 0]^T$ m; upward thrust: $[0, 0, -5]^T$ N. Ignore reaction torque initially.
- The cross product in one frame gives $[-0.75, 1.00, 0]^T$ N·m: lifting the right side gives negative roll, and lifting the nose gives positive pitch, consistent with the physical directions.
- An angled arm's length differs from its forward/lateral projections. Moving a rotor changes leverage; renumbering motors only changes order. Add reaction torque separately.
- Use the method from Section 4.3's cross-product example, now with unequal forward and lateral moment arms.



Top view: thrust out of the page

Position projections determine moment arms

The position vector sets roll and pitch torque for a given thrust.

4.8.1 Multicopter UAVs: Summing Rotor Forces and Torques

Sum Rotor Loads, Then Compare Thrust Sharing

- Each rotor thrust acts along negative z_b, with $T_i = c_{\mathrm{T}}\omega_i^2$. Its roll and pitch contributions are $-y_i T_i$ and $x_i T_i$.
- Reaction-torque coefficient: c_{M}. Choose $s_i = \pm 1$ by the reaction torque on the body. Each column represents one physical motor; use individual coefficients when they differ.

- With symmetry, the same 2 kg mass, and g = 9.8 m/s², total thrust is 19.6 N: 4.9 N per rotor for four rotors or 3.2667 N for six. Convert thrust shares to throttle through each motor's input–thrust relation.

$$[T, M_x, M_y, M_z]^{\top} = \sum_{i=1}^{n} [c_{\mathrm{T}},\ -y_i c_{\mathrm{T}},\ x_i c_{\mathrm{T}},\ s_i c_{\mathrm{M}}]^{\top} \omega_i^2$$

Layout changes the torque mapping; rigid-body equations still receive resultant force and torque.

4.8.1 Multicopter UAVs: Layout and Control Allocation

Use One Rotor Matrix for Synthesis and Allocation

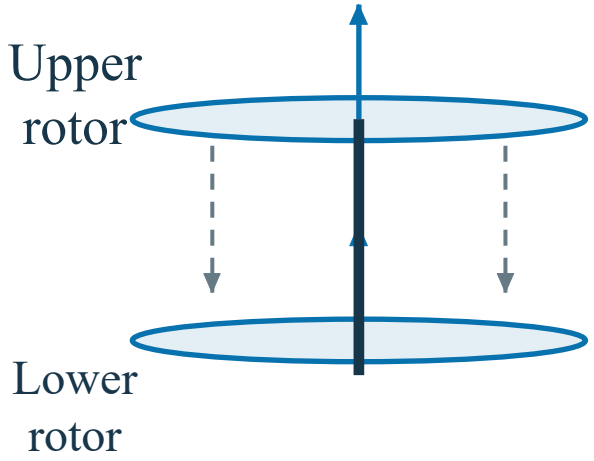
- Plus layouts place arms on the body axes; X layouts place them diagonally. X layouts offer a clear forward view and camera space and are now predominant. Equal arm lengths still give different moment arms and motor numbering.
- **Forward:** for near-vertical rigid rotor axes, no saturation, and a valid thrust square law, $v = Bq$, $q_i = \omega_i^2$. Columns of B depend on position, spin, c_{T}, and c_{M}; v contains total thrust and three-axis torque.
- **Inverse:** given target v_d, solve $Bq = v_d$ for bounded q, then use calibrated motor mappings to obtain commands. Exact realization requires full rank, reachability, and no saturation. With identical normalization, a smaller condition number of B means less sensitivity to disturbances. See Section 4.3's inverse-mapping and feasible-set page.
- **Template:** RflySim adapts conventional 3–8-rotor layouts through the airframe parameter. Custom layouts require matching changes to model mapping and autopilot control allocation.

Synthesize loads; invert to rotor inputs. Rebuild the matrix after layout changes.

4.8.1 Multicopter UAVs: Coaxial Wake Interference

Coaxial Octocopters Add Rotor Interaction

- Two rotors on one arm have similar lateral moment arms. The lower rotor lies in the upper rotor's wake; isolated-rotor thrust laws may no longer apply.
- The 10%–20% estimate here concerns efficiency loss. Determine thrust loss from the efficiency definition, equal-speed or equal-power conditions, and paired-rotor bench data.
- Coaxial layouts reduce lateral size. Evaluate efficiency, noise, structure, and failure margins individually before selection.



Upper-rotor wake changes lower-rotor inflow

Coaxial wake interference

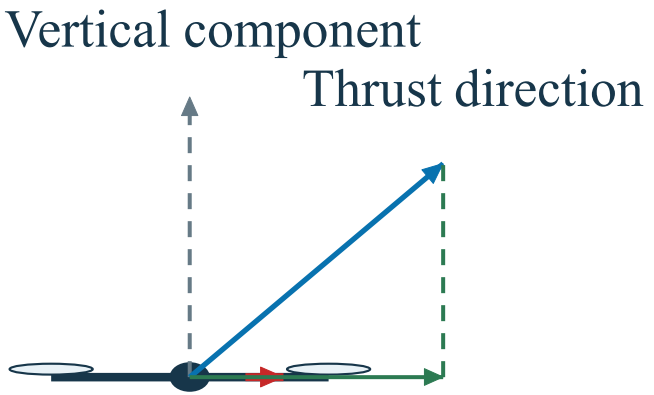
Coaxial rotors share nearly the same lateral position, but may not follow isolated-rotor thrust laws.

4.8.1 Multicopter UAVs: Tilting the Thrust Axis

A Tilted Rotor Needs Both Direction and Position

- Unit vector $\mathbf{a}_i$ gives the thrust direction: $\mathbf{F}_i = T_i \mathbf{a}_i$. Tilting changes vertical support and forward thrust together.

- A tilting mechanism also needs servo angle, dynamics, and limits. Update its direction each step, then add moment-arm torque and reaction torque $\mathbf{Q}_i$.



The same thrust magnitude, a different direction

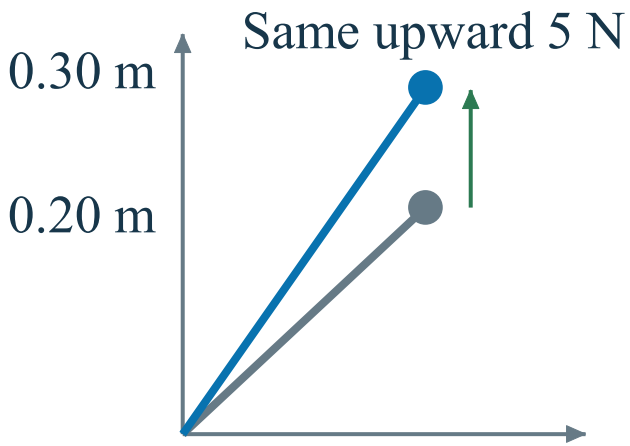
$$\mathbf{F}_b = \sum_i T_i \mathbf{a}_i, \qquad \mathbf{M}_b = \sum_i (\mathbf{r}_i \times T_i \mathbf{a}_i + \mathbf{Q}_i)$$

Changing the axis redistributes thrust and changes resultant torque.

4.8.1 Multicopter UAVs: Moving One Rotor

Move One Rotor: Predict Which Torque Changes

- Keep upward thrust at 5 N and lateral position at 0.15 m. Move the rotor forward from 0.20 to 0.30 m; keep all other rotors and inputs unchanged.
- Roll torque remains -0.75 N·m; pitch torque rises from 1.00 to 1.50 N·m. Total thrust is unchanged. Geometry alone changes resultant torque.
- Record both position vectors, torques, and expected rotation. If you also retrim, record the changed input as a separate experimental condition.



Change only the forward moment arm

The same input can preserve resultant force while a changed moment arm changes torque.

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4.8.2 Fixed-Wing UAVs

Textbook: Sec. 4.2.5.2

4.8.3 Unmanned Ground Vehicles

Textbook: Sec. 4.2.5.3

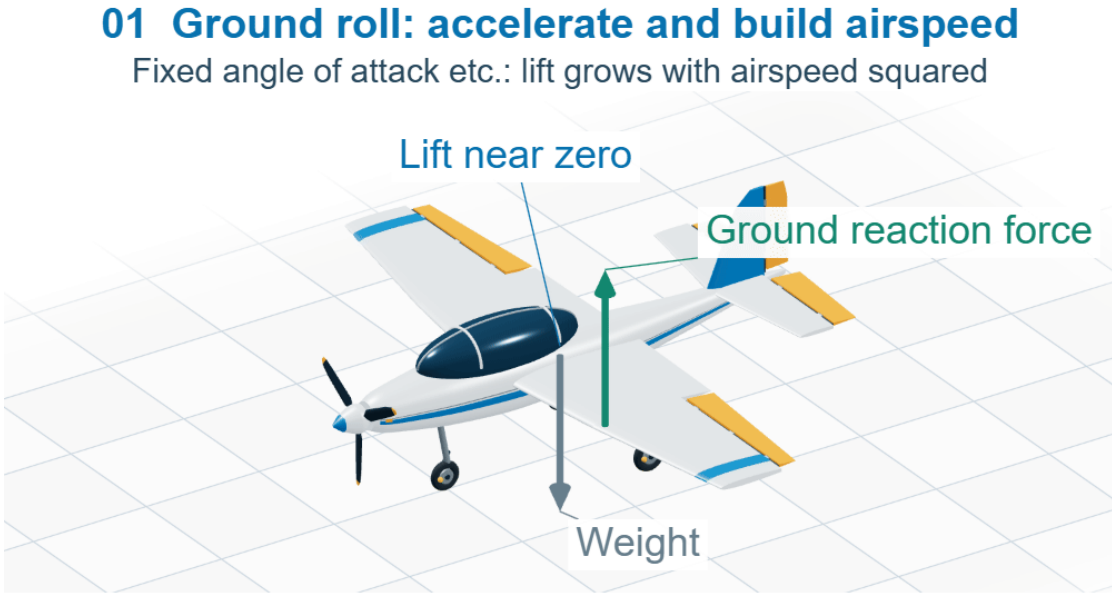
4.8.4 Other Vehicles and Model Selection

Textbook: Secs. 4.2.5.4 and 4.3.2

4.8.2 Fixed-Wing UAVs: Wing Support and Propulsion

Wings Support Weight; Propulsion Maintains Airflow

- Conventional wings support weight in relative airflow; propulsion mainly overcomes drag. Control surfaces generate attitude torques by changing local aerodynamic forces.
- Throttle changes propulsion first, then wing loads through airspeed. Pitching up first changes attitude; the flight path also depends on airspeed and current forces.
- Watch ground roll, liftoff, and turn. Ground support vanishes after liftoff; lift direction changes with flight state. The teaching illustration assumes no wind.



From ground support to aerodynamic support

Airspeed links propulsion/wings/control surfaces; four vertical thrusts cannot replace them.

4.8.2 Fixed-Wing UAVs: Airspeed and Airflow Angles

Compute Airspeed, Angle of Attack, and Sideslip

- **Relative velocity:** ground $[15,0,0]^{\mathrm{T}}$ minus wind $[5,2,0]^{\mathrm{T}}$ m/s in north-east-down (NED) coordinates gives $\mathbf{v}_{a,e} = [10,-2,0]^{\mathrm{T}}$ m/s, magnitude 10.198 m/s.
- **Body-frame conversion:** set $\phi = \psi = 0$ and pitch $\theta = 5.71°$. Then $\mathbf{v}_{a,b} = R^{\mathrm{T}}\mathbf{v}_{a,e} = [9.950,-2,0.995]^{\mathrm{T}}$ m/s. Rotation preserves the magnitude.
- **Airflow angles:** $V_a = 10.198$ m/s, $\alpha = \mathrm{atan2}(0.995,9.950) = 5.71°$, $\beta = \arcsin(-2/10.198) = -11.31°$. With zero roll and horizontal airflow, angle of attack equals pitch.
- Use radians in trigonometric calculations. At zero airspeed the angles are undefined; use a low-speed branch to avoid division by zero.

$$\mathbf{v}_{a,b} = R^{T}(\mathbf{v}_{e} - \mathbf{v}_{w,e}), \quad \alpha = \mathrm{atan2}(w_a, u_a), \quad \beta = \arcsin(v_a/V_a)$$

Aerodynamics depends on relative air velocity; subtract velocities in the same frame first.

4.8.2 Fixed-Wing UAVs: Dynamic Pressure and Lift

Quarter Dynamic Pressure, Quadruple Lift Coefficient

- Dynamic pressure: $\bar{q} = \rho V_a^2/2$. Teaching conditions: $m = 2$ kg, $S = 0.5$ m², $\rho = 1.225$ kg/m³, $g = 9.8$ m/s²; assume approximately level, wing-supported flight.
- At 15 m/s, $\bar{q} = 137.8125$ Pa and required $C_L = 0.2844$. At 7.5 m/s, they are 34.4531 Pa and 1.1378. Check maximum wing lift coefficient to assess feasibility and stall.
- S is reference area; $\bar{c}$ is aerodynamic chord. C_L, C_m are dimensionless. At fixed coefficients, lower dynamic pressure reduces force and torque; surface limits restrict compensation.

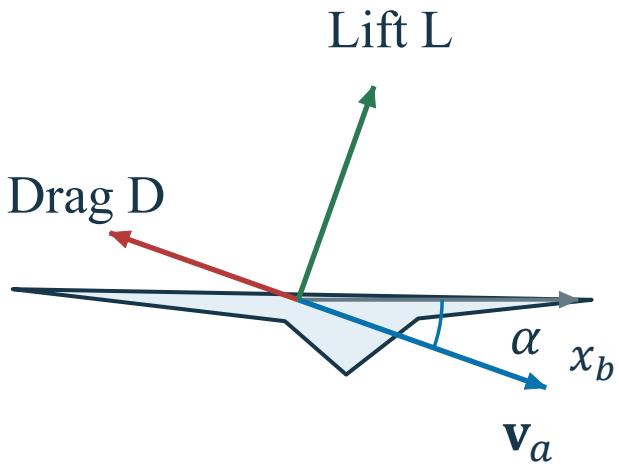
$$L = \bar{q}SC_L, \quad M_y = \bar{q}S\bar{c}C_m, \quad C_{L,\text{req}} = mg/(\bar{q}S)$$

Dynamic pressure scales with speed squared and sets wing and control-surface load scales.

4.8.2 Fixed-Wing UAVs: Transforming Lift and Drag

Define Lift and Drag in Airflow Axes, Then Transform

- Drag opposes air-relative velocity; lift is perpendicular to it in the airflow plane. When nose and airflow differ, rotate the forces to obtain body-axis components.
- Compute aerodynamic forces/torques from airspeed, angles, and surface deflections. Rotate to FRD, add propulsion and other nongravitational loads, and feed the rigid-body equations.
- Count gravity once under the common convention. If a legacy template already adds it at the resultant-force input, adjust that boundary during migration to avoid double counting.



Side view: airflow forces

Lift and drag are defined relative to airflow

Express aerodynamic loads in the body frame before combining them with propulsion loads.

4.8.2 Fixed-Wing UAVs: Aerodynamic Coefficient Scales

Separate Angle, Surface, and Rate Effects in Coefficients

- Near an operating point, write $C_L = C_{L0} + C_{L\alpha}\alpha + C_{L\delta_e}\delta_e + \cdots$. The constant, angle-of-attack, and elevator terms represent distinct contributions.

- Let b be wingspan and $\bar{c}$ mean aerodynamic chord. Use these lengths and airspeed to normalize body rates p, q, r. These dimensionless rates enter aerodynamic damping terms; retain the scale factors.
- InitData.m supplies geometry, inertia, and aerodynamic coefficients. Read it with the defining equations: dynamic pressure $\overline{q}$, pitch rate q, and dimensionless $\hat{q}$ have different meanings and units.

$$\hat{p} = \frac{bp}{2V_a}, \qquad \hat{q} = \frac{\bar{c}q}{2V_a}, \qquad \hat{r} = \frac{br}{2V_a}$$

Coefficient models define how inputs change loads; match their units and validity ranges.

4.8.2 Fixed-Wing UAVs: Conventional and Flying-Wing Surfaces

Different Layouts Assign Control to Different Surfaces



Conventional Fixed-Wing



Flying-Wing Configuration



Compound VTOL UAV

Servo 1: aileron → roll
Servo 2: elevator → pitch
Servo 3: rudder → yaw
Motor 1: throttle → propulsion

Servos 1/2: elevons
Same direction → mainly pitch
Differential → mainly roll
Motor 1: throttle → propulsion

Primary: motors 1–4, rotors
Auxiliary: servos 1–4, surfaces
Auxiliary: motor 5, cruise throttle
Both groups cooperate in transition

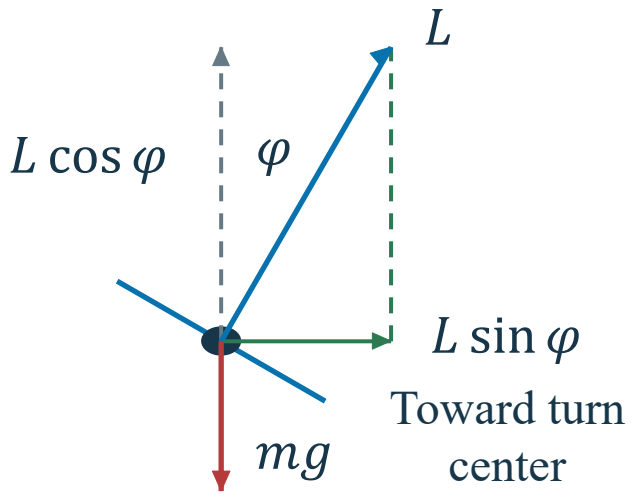
Figure 4.14 (detail): fixed-wing control channels; numbering follows the selected example.

Layout determines mixing; the same control intent can require different surface motion.

4.8.2 Fixed-Wing UAVs: Loiter and Coordinated Turns

Banked Lift Supplies Centripetal Force in a Loiter

- **Station keeping:** conventional aircraft maintain forward airspeed, usually loitering around the target instead of hovering.
- **Coordinated turn:** bank φ tilts lift. $L \sin \varphi$ supplies centripetal force; $L \cos \varphi = mg$ maintains altitude. Greater drag requires added thrust.
- **Example:** $V = 15$ m/s and $\varphi = 30^\circ$ give $L/(mg) = 1/\cos \varphi = 1.155$, and turn radius $R = V^2/(g \tan \varphi) = 39.8$ m.



Lift components in a coordinated turn (rear view)

A larger bank angle reduces turn radius and increases required lift and thrust.

4.8.2 Fixed-Wing UAVs: Airspeed and Flying-Wing Recovery

Measure Airspeed; Plan Flying-Wing Launch and Recovery

- Airspeed sensing measures relative airflow, not ground speed. Combine it with attitude, pressure, and wind estimates to constrain angle of attack and dynamic pressure.
  At low airspeed, surface authority and coefficients are unreliable; account for mounting and calibration.
- **Conversion:** the sensor measures dynamic pressure $\bar{q}$, with $V_a = \sqrt{2\bar{q}/\rho}$. For $\bar{q} = 137.8$ Pa and $\rho = 1.225$ kg/m³, airspeed is 15.0 m/s. At local $\rho = 1.0$ kg/m³, it is about 16.6 m/s.

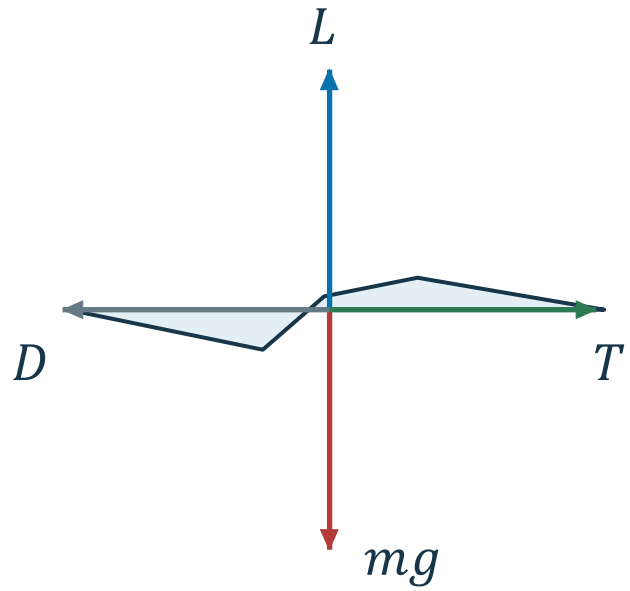
- Flying wings mix pitch and roll through paired elevons. Catapult or hand launch establishes sufficient airspeed; glide or parachute recovery depends on airframe design and site conditions.

Airspeed sensing and launch/recovery depend on valid aerodynamic conditions.

4.8.2 Fixed-Wing UAVs: Initial State and Cruise Trim

Initialization Sets a Starting Point; Solve Trim Separately

- Wind-free straight level cruise: approximately $L = mg, T = D$, zero net torque on each axis. Jointly solve compatible angle of attack, surface deflections, and throttle; position still advances.
- Current fixed-wing templates e2/e5 use mass 8.16466266 kg, initial forward speed 0.001 m/s, and zero position/attitude. These are startup settings; solve 15 m/s cruise trim separately.
- The micro-aircraft template e5 also needs parameter scripts, MavLinkStruct (the root-port MAVLink bus definition), and Aerospace Blockset. Ground takeoff additionally involves contact and acceleration.



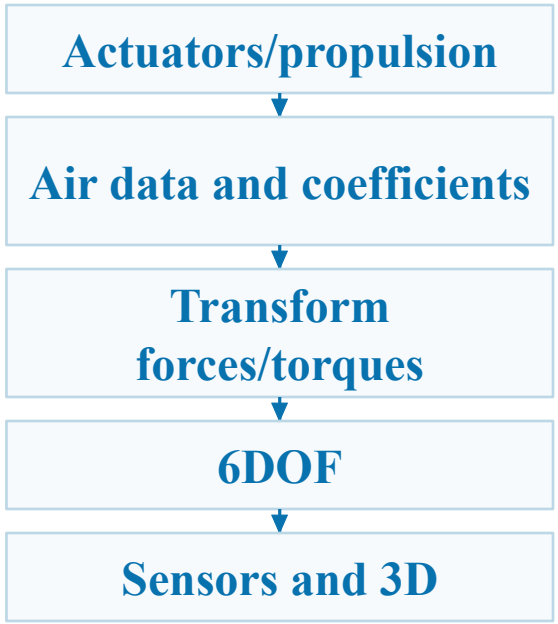
Force and torque balance in cruise

Forward velocity alone defines an initial state; balance also requires suitable attitude and inputs.

4.8.2 Fixed-Wing UAVs: Equation Blocks in the Model

Locate Each Equation in the Supplied Fixed-Wing Model

- AircraftMathworks.slx in 1.BasicExps/e2_FixWingModelCtrl contains actuator mapping, Actuator Model, Motor Model, and Small Fixed Wing UAV Dynamics.
- Inside the dynamics block, Compute Air Data calculates airspeed and angles; Aerodynamic Forces and Moments calculates loads. Rotation and 6DOF then advance states.
- The output chain sends states to sensors and 3D display. Trace inputs, loads, and states in sequence to distinguish aerodynamic errors from sensing or display errors.



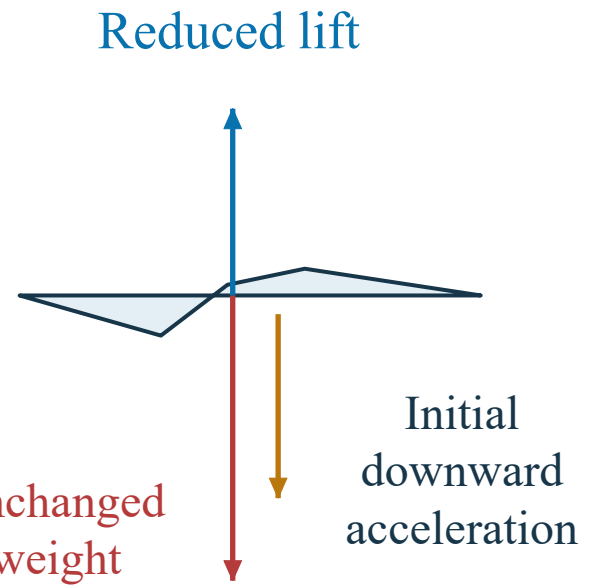
Fixed-wing equation responsibilities

Air data, load synthesis, and motion integration each have a defined place in the model.

4.8.2 Fixed-Wing UAVs: Observable Migration Predictions

Predict an Observable Change Before an Integrated Run

- At a declared trim point, hold density, mass, inputs, and initial state fixed. Predict the immediate vertical resultant after reducing the lift coefficient, then run the full model.
- Log airspeed, angle of attack, surface deflections, attitude, and altitude. The controller subsequently changes the surfaces; examine the immediate response to isolate the aerodynamic parameter's effect.
- Deliver a table: parameter | port | initial state | prediction | measurement. See Section 4.11 for execution. Its vehicle-migration task permits either fixed-wing or ground-vehicle migration.



Immediate effect of reducing lift from trim

Connect parameter changes to loads and outputs so that migration results are explainable.

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Textbook: Sec. 4.2.5.3

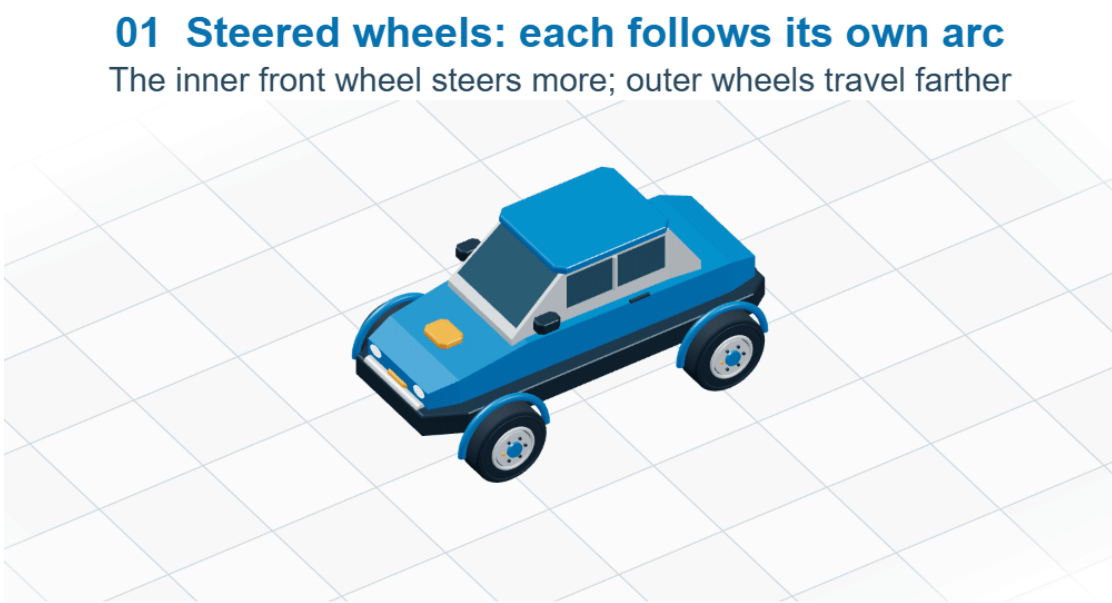
4.8.4 Other Vehicles and Model Selection

Textbook: Secs. 4.2.5.4 and 4.3.2

4.8.3 Unmanned Ground Vehicles: Contact and Planar Motion

Contact Constraints and Low-Speed Kinematic Predictions

- Ground support carries weight; tires provide drive force and lateral constraints. On flat ground, at low speed and small sideslip, use position/heading kinematics.
- Both vehicle models contain Ground Model, Force and Moment, and 6DOF. Drive and steering first generate contact forces; integration then produces velocity.
- Wheel steering, track skidding, and omnidirectional wheels differ. Animation coordinates: forward-left-up; steering signs follow this chapter's NED convention.



Different running gear uses different contact mechanisms

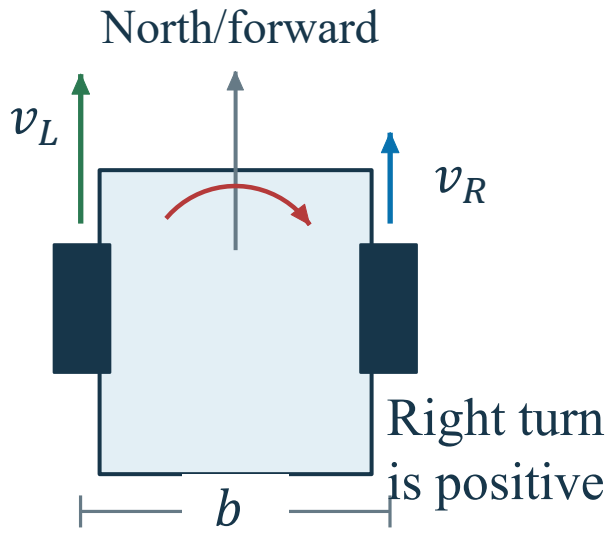
Planar motion needs contact conditions; deleting altitude from six-DOF equations is not enough.

4.8.3 Unmanned Ground Vehicles: Wheel Speeds and Heading

Average Wheel Speed Advances; Left Minus Right Turns Right

- In NED/FRD, right turns viewed from above are positive; both wheel speeds are positive forward. For track width b and wheel radius r_w, no slip gives $v_L = r_w\omega_L$ and $v_R = r_w\omega_R$.
- Forward speed $v = (v_L + v_R)/2$; heading rate $r = (v_L - v_R)/b$. A faster left wheel turns the nose right. Track width differs from wheelbase.
- Project forward velocity north/east using heading, then integrate. Wheel speeds are given here; motor lag and friction belong in the dynamics model.

$$\dot{x}_N = v\cos\psi, \quad \dot{y}_E = v\sin\psi, \quad \dot{\psi} = r$$



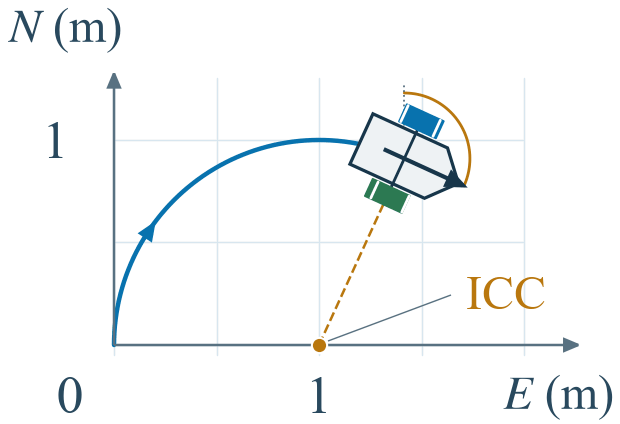
Wheel speeds and NED heading

Heading increases from north toward east, so a faster left wheel gives positive yaw rate.

4.8.3 Unmanned Ground Vehicles: Differential-Drive Arc

Compute Two-Second Arc Displacement from Wheel Speeds

- Track width 0.4 m; wheel radius 0.1 m. Left/right rates: 12/8 rad/s. Start at zero position and heading: $v = 1$ m/s, $r = 1$ rad/s.
- Constant wheel speeds give $\psi = rt$. At 2 s: north 0.9093 m, east 1.4161 m, heading 2 rad. The 2 m path length differs from straight-line displacement.
- For $r = 0$, use the straight branch: north vt, east 0; avoid division by zero. Assume no slip here; model actual drive and sideslip separately.



$t = 2.00$ s
$N = 0.9093$ m
$E = 1.4161$ m
$\psi = 2.00$ rad

L 12 rad/s
R 8 rad/s

A faster left wheel produces a right-turn arc

$$x_N = (v/r)\sin(rt)$$

$$y_E = (v/r)[1 - \cos(rt)]$$

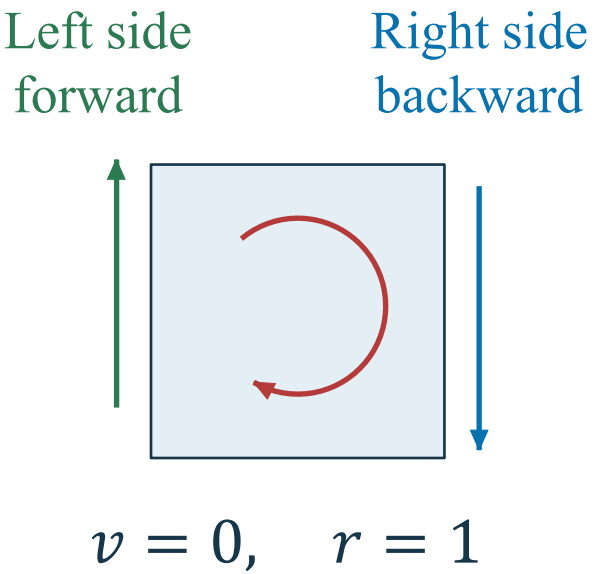
Integrate heading first, then the north/east velocities that change with heading.

4.8.3 Unmanned Ground Vehicles: In-Place Rotation

Equal and Opposite Wheel Speeds Produce a Pivot Turn

- For $v_L = 0.2$ m/s, $v_R = -0.2$ m/s, and $b = 0.4$ m, average forward speed is 0 and heading rate is 1 rad/s.

- One side advances while the other reverses, keeping the ideal center fixed. Real four-wheel differential-drive vehicles often exhibit lateral tire slip, friction losses, and changing motor loads.
- Use pivot turns as functional tests. Tire forces, power use, and response buildup require a dynamics model or measurements.



$$v = 0, \quad r = 1$$

Opposite wheel motion, no center translation

Zero average speed can coexist with a nonzero heading rate.

4.8.3 Unmanned Ground Vehicles: Fast Turns and Sideslip

Fast Turns Can Violate the Low-Speed No-Slip Assumption

① Lateral demand

$a_{\text{lat}} = v^2/R_c$. At fixed radius, doubling speed quadruples lateral demand.

② Friction limit

Teaching values $\mu = 0.5$, $g = 9.8$ m/s², and $R_c = 2$ m give $v \le \sqrt{\mu g R_c} = 3.1305$ m/s.

③ Compare

5 m/s exceeds the limit: contact cannot supply the required lateral force, so the ideal no-slip arc no longer holds.

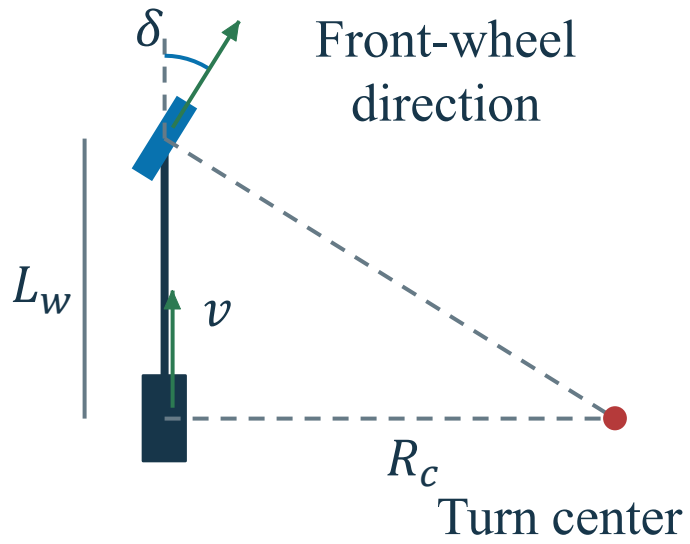
- **Assumptions:** ignore load transfer, longitudinal drive, and tire details. This estimate only flags possible no-slip failure; full-envelope analysis needs tire characteristics.

The ideal arc fails when required lateral force exceeds contact capability.

4.8.3 Unmanned Ground Vehicles: Ackermann Bicycle Model

A Bicycle Model Captures Low-Speed Ackermann Geometry

- Equivalent front steering angle δ is positive right; wheelbase is L_w. At low speed without sideslip, $r = v\tan\delta / L_w$, where v is forward speed at the rear-axle center.
- The inner wheel follows a smaller circle and needs a larger steering angle. The centerline bicycle model summarizes both sides' geometry, omitting tire and sideslip details.
- At zero speed, heading rate is zero. Ackermann vehicles cannot pivot in place and have larger turn radii, but resemble road-car motion and suit higher-speed trajectory tracking.



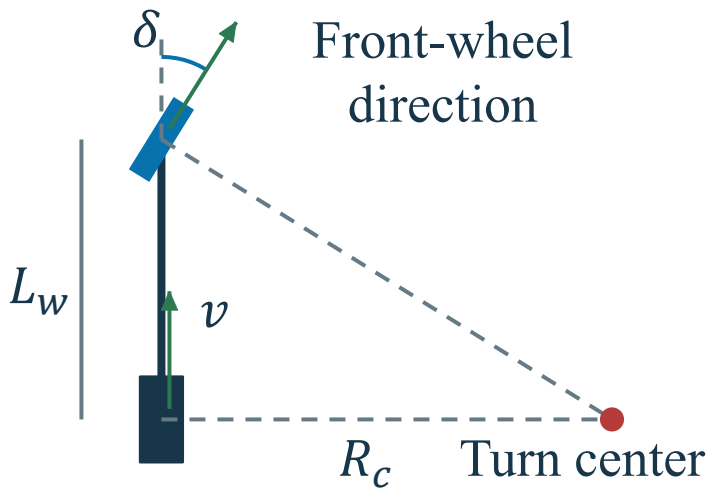
Steering angle, wheelbase, and turning radius

Steering sets curvature; rear-axle-center speed sets progress along the arc.

4.8.3 Unmanned Ground Vehicles: Wheelbase and Turn Radius

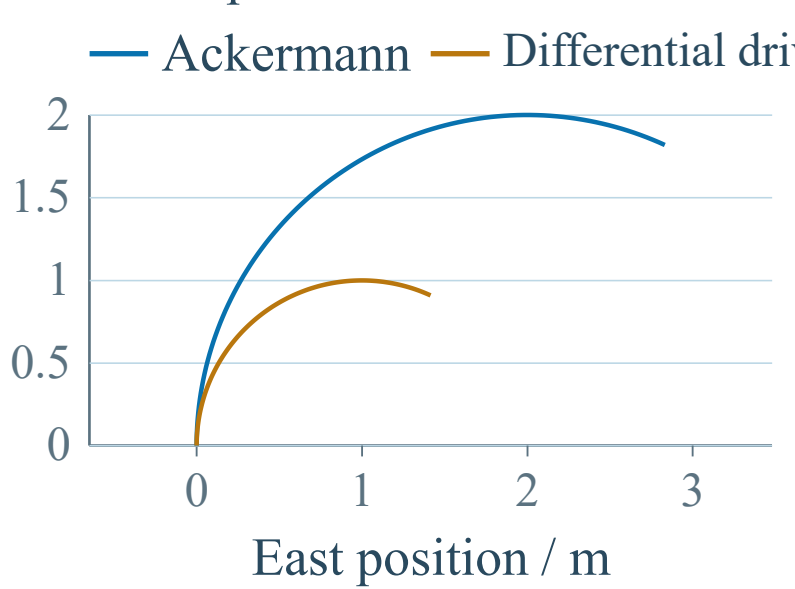
Ackermann: Find Radius from Wheelbase and Steering

- Teaching: $L_w = 1$ m, right steering $\delta = 26.565°$, rear-axle $v = 2$ m/s; zero initial state; $\tan\delta = 0.5$.



Steering sets curvature; at fixed radius, speed sets heading rate.

Radius: 2 m; heading rate: 1 rad/s.
At 2 s: north 1.8186 m, east 2.8323 m, heading 2 rad.
At equal heading rate, doubling radius doubles displacement.



Analytical arcs for two specified parameter sets

- Curve differences follow the specified speeds and geometry.

4.8.3 Unmanned Ground Vehicles: Offline Trajectory Comparison

Run the Script to Predict Vehicle Migration

- **Folder:** [installation directory]/RflySimAPIs/4.RflySimModel/1.BasicExps/e6_ModelingLearningLab/04_VehicleKinematics/. Start with Readme.pdf.
- Run with base MATLAB. Change to this folder and enter metrics = vehicle_migration_baseline;. Results go to outputs; if no figure window opens, open the PNG files there.
- **Checks:** PNGs compare analytical and Euler trajectories. In vehicle_migration_results.json, the differential-drive endpoint is about north 0.9093 m, east 1.4161 m. For steps 0.02/0.01 s, position_error_m is about 0.0168/0.0084 m and error_ratio is about 2.
- **Scope:** these results are offline planar kinematics. Compare tire and actuator responses separately in the platform model.

Analytical paths and discrete integration give a numerical baseline before platform integration.

Chapter Outline

Typical Unmanned Vehicle Modeling and Extensions

Chapter 4
Vehicle Motion Modeling and Simulation
4.1 Modeling Fundamentals and Kinematics
4.2 Rigid-Body Dynamics and Solvers
4.3 Propulsion, Forces, and Observations
4.4 Trim, Linearization, and Dynamics
4.5 Multicopter Modeling and Simulation
4.6 Measurement and Static Identification
4.7 Dynamic Identification and Refinement
4.8 Typical Vehicles and Extensions
4.9 Modeling Tools and Deployment
4.10 API and SDK Modeling Interfaces
4.11 Examples and Integrated Practice
4.12 Exercises and Course Projects

4 Units in This Section

4.8.1 Multicopter UAVs

Textbook: Sec. 4.2.5.1

4.8.2 Fixed-Wing UAVs

Textbook: Sec. 4.2.5.2

4.8.3 Unmanned Ground Vehicles

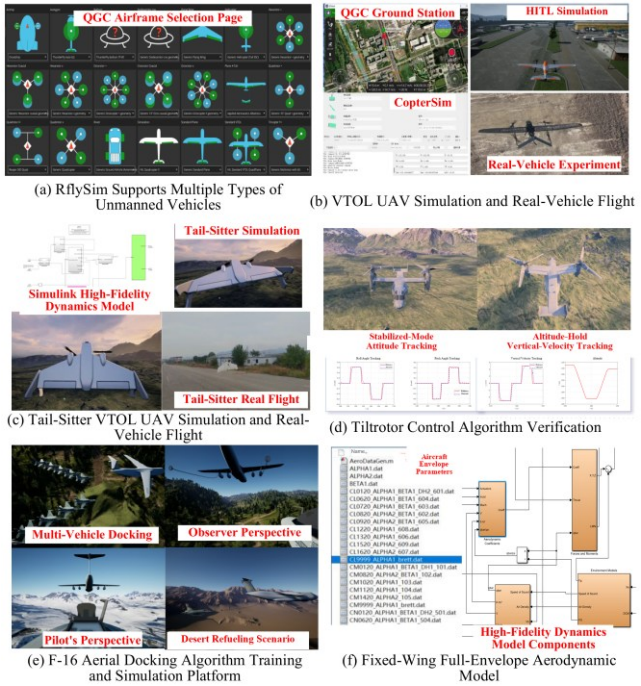
Textbook: Sec. 4.2.5.3

4.8.4 Other Vehicles and Model Selection

Textbook: Secs. 4.2.5.4 and 4.3.2

4.8.4 Other Vehicles and Model Selection: Added Physics

Advanced Cases: Added Physics and Validation



(a) RflySim Supports Multiple Types of Unmanned Vehicles
(b) VTOL UAV Simulation and Real-Vehicle Flight
(c) Tail-Sitter VTOL UAV Simulation and Real-Vehicle Flight
(d) Tiltrotor Control Algorithm Verification
(e) F-16 Aerial Docking Algorithm Training and Simulation Platform
(f) Fixed-Wing Full-Envelope Aerodynamic Model

Figure 4.15 Advanced Cases

(a) Vehicle types and control airframes

(b) VTOL: vertical takeoff/landing, simulation/flight

(c) Tail-sitter: large-angle body transition

(d) Tiltrotor: mechanism angle and tracking tests

(e) F16: task and viewing perspectives

(f) Aerodynamic model: data and validity range

Next: hybrid-wing transition, tail-sitters/tiltrotors, F16 and full-envelope aerodynamics, then buoyancy, helicopter pitch, and slung-load/trailer constraints.

Different forms and tasks introduce different states, forces, and validation conditions.

4.8.4 Other Vehicles and Model Selection: Figure 4.15(a)(b)

Multiple Vehicle Types: From VTOL Simulation to Flight

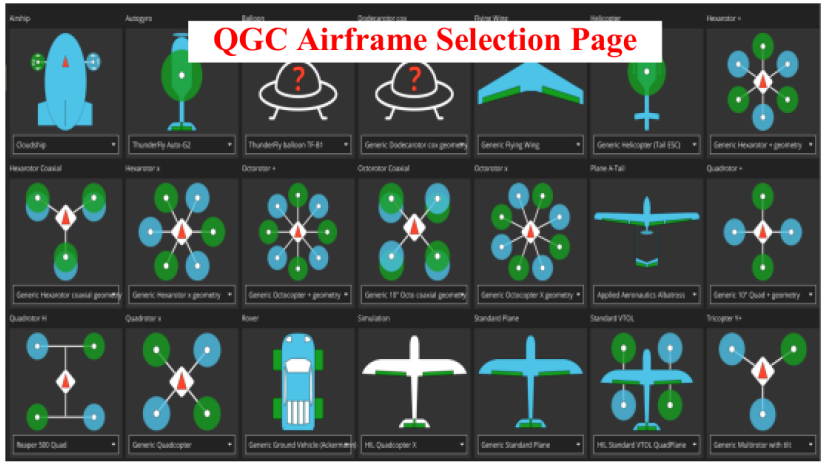


Figure 4.15(a) Supported vehicle types



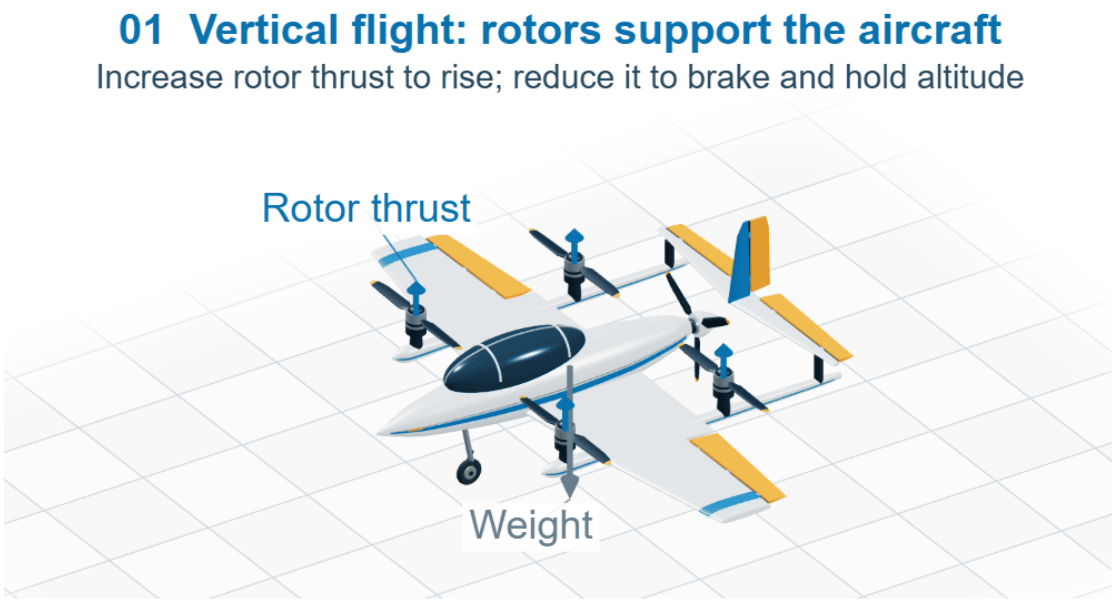
Figure 4.15(b) VTOL: simulation to real flight

- **Panel (a):** QGroundControl (QGC) lists multicopter, fixed-wing, VTOL, and ground-vehicle airframes. Selecting an airframe determines PX4's actuator configuration.
- **Panel (b):** the same VTOL progresses through QGC, CopterSim, and hardware-in-the-loop (HITL; HIL in the textbook) simulation to real flight. See the hybrid-wing load-transfer page for transition forces.

4.8.4 Other Vehicles and Model Selection: Hybrid-Wing Load Transfer

Rotors and Wings Share Weight During Transition

- At low speed, VTOL support comes mainly from rotors. As propulsion builds airspeed, wings carry more weight. Rotors and struts add drag in cruise.
- In nearly level, quasi-steady flight, $T_{\text{rotor},\uparrow} + L \approx mg$. This is shared support of one vehicle, rather than alternating motion states.
- Lift rotors support weight; cruise thrust builds airspeed. Low-speed surface authority is weak. Blend thrust/surface allocation continuously in transition; check torque and margins.



Rotors and wings share support during transition

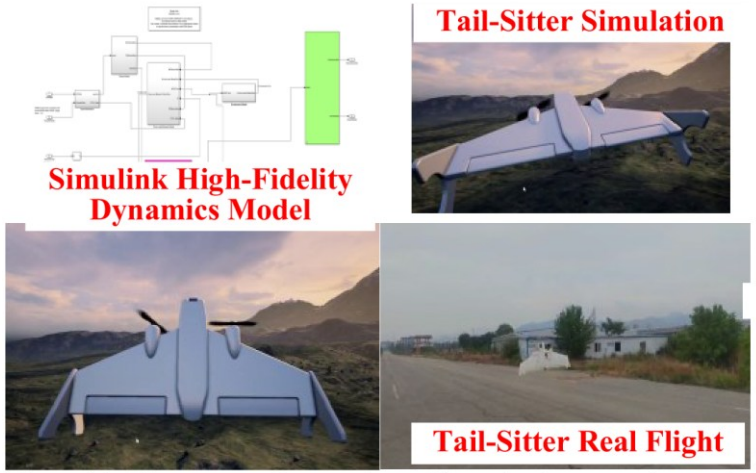
Transition changes forces continuously; switching between unrelated models cannot represent it.

4.8.4 Other Vehicles and Model Selection: Tail-Sitter vs. Tiltrotor

Tail-Sitter Body Rotation and Tiltrotor Mechanism Angles

- A tail-sitter rotates its whole body from near vertical to forward flight. Wings and sensors rotate together; the attitude model must handle large angles.

- A tiltrotor adds mechanism angles relative to the fuselage. These change thrust direction and add servo dynamics, limits, and coupling; body attitude alone is insufficient.
- The textbook pairs tail-sitter simulation and real flight. Match inputs and conditions in comparisons; evaluate transition accuracy using data from the entire maneuver.



(c) Tail-Sitter VTOL UAV Simulation and Real-Vehicle Flight

Figure 4.15 Advanced Cases (tail-sitter detail)

Transition architecture determines which angles are body states and which are mechanism states.

4.8.4 Other Vehicles and Model Selection: Figure 4.15(d) Tiltrotor Tracking

Test Tiltrotor Control with Attitude and Velocity Tracking

Stabilized mode | **Altitude-hold mode**

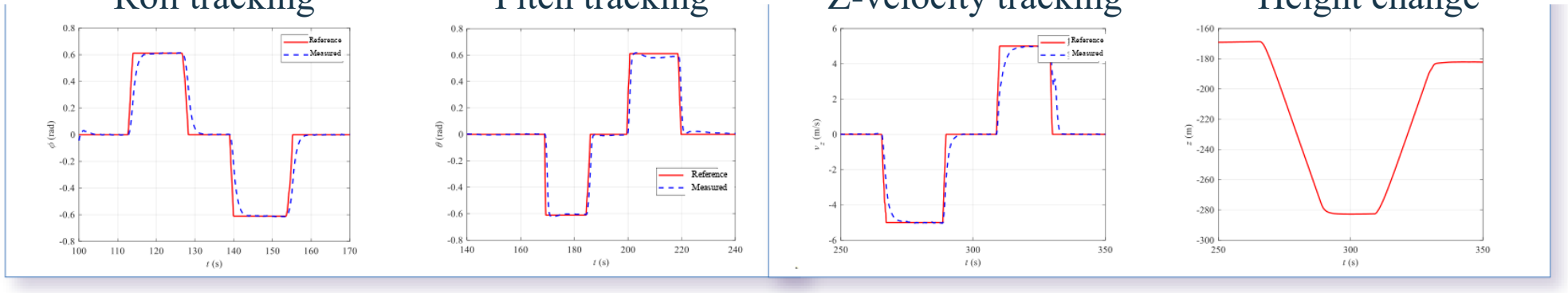


Figure 4.15(d) Tiltrotor control validation (tracking-curve detail)

- **Red solid:** desired; blue dashed: actual. Vertical axes: roll/pitch (rad), Z velocity (m/s), and height z (m). Horizontal axis: time (s).
- Attitude follows square-wave commands with slight lag. Z velocity follows ±5 m/s steps; more negative z means climbing. See the tail-sitter/tiltrotor comparison for mechanism angles.

4.8.4 Other Vehicles and Model Selection: F16 and Aerodynamic Coverage

F16 Scenes and Full-Envelope Aerodynamics



(e) F-16 Aerial Docking Algorithm Training and Simulation Platform

(f) Fixed-Wing Full-Envelope Aerodynamic Model

Figure 4.15 Advanced Cases (F16 and full-envelope model details)

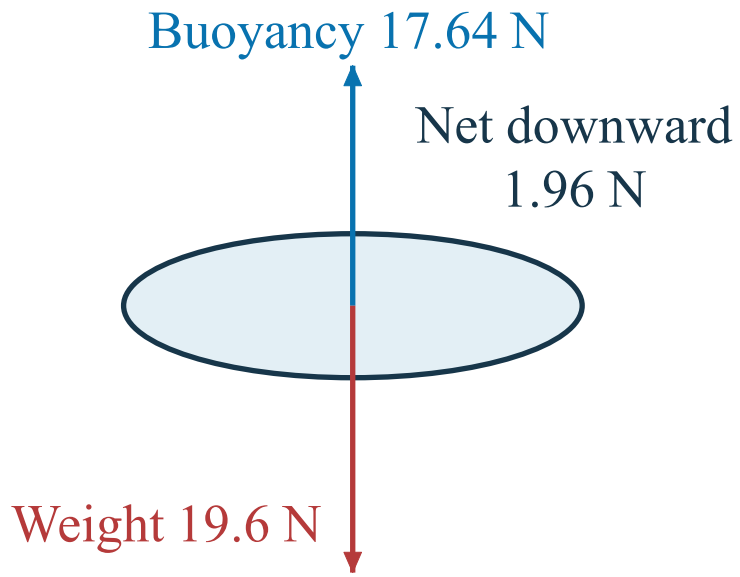
- The F16 scene supports task interaction and observation. Full-envelope aerodynamic data determines loads at a given state; visual complexity does not establish aerodynamic accuracy.
- Query tables by angle of attack, sideslip, Mach number, and surface deflection. Check interpolation, reference scales, and out-of-table behavior; broad coverage still needs independent validation conditions.

Check task visuals and physical accuracy separately; aerodynamic data bounds maneuvers.

4.8.4 Other Vehicles and Model Selection: Marine Forces

Hydrodynamics Adds Immersion, Buoyancy, and Added Mass

- Surface vessels use water-relative velocity for drag. Submerged volume and center of buoyancy affect buoyancy and restoring torque; moving surrounding fluid also adds inertia.
- **Unmanned underwater vehicle (UUV) example:** $m = 2$ kg, $V = 0.0018$ m³, $\rho_w = 1000$ kg/m³, $g = 9.8$ m/s²; buoyancy $B = \rho_w g V = 17.64$ N.
- Ignoring added mass and damping, $a_D = (mg - B)/m = 0.98$ m/s². Neutral buoyancy ensures vertical balance only; attitude still depends on the centers of buoyancy and mass.



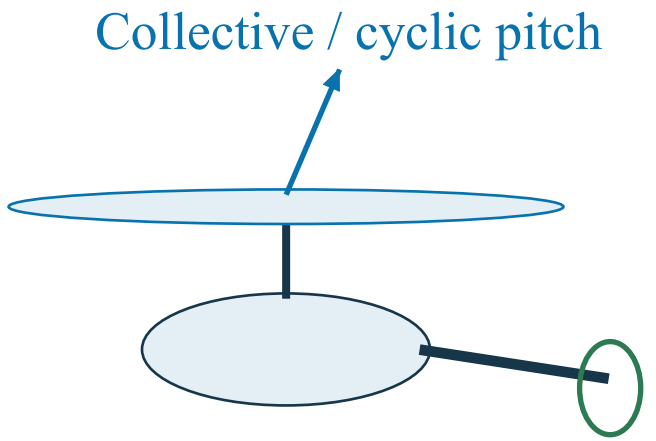
Independent underwater-vehicle heave example

Marine motion models must describe propulsion, immersion, and restoring attitude effects.

4.8.4 Other Vehicles and Model Selection: Helicopter Blade Pitch

Helicopters Control Rotor Loads Through Blade Pitch

- Collective changes all blade pitches together. Cyclic varies pitch with azimuth to redirect rotor-disk loading. Rotor-speed control is only part of the mechanism.
- A tail rotor or another mechanism provides antitorque and yaw control. Retain flapping, induced flow, and mechanism dynamics according to the task's frequency band.
- 2.AdvExps/e8_Helicopter provides model/control examples. Start low-frequency trajectory studies with a low-order approximation, then validate with data in the target band.



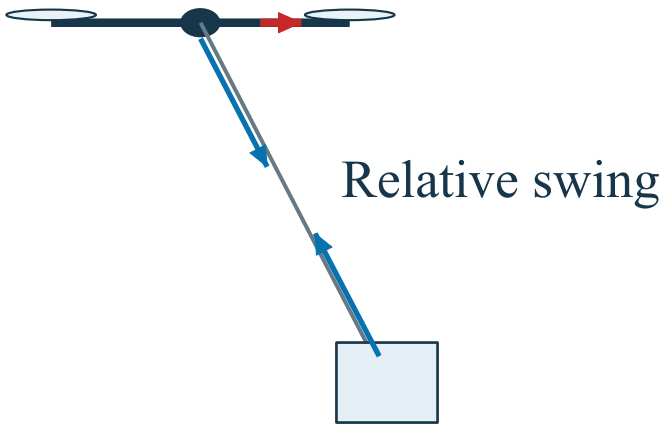
Collective, cyclic, and tail rotor

Collective, cyclic, and tail-rotor action add rotor aerodynamics and mechanism states.

4.8.4 Other Vehicles and Model Selection: Loads, Tethers, and Trailers

Slung Loads, Tethers, and Trailers Connect Multiple Bodies

- A fixed payload can be included in mass, center of mass, and inertia. A slung load swings relative to the body, requiring load position or swing angles and coupling through rope tension.
- An ideal flexible rope pulls but cannot push; slack and taut constraints differ. Tethers may also have a fixed anchor, variable length, and rope mass.
- A trailer adds articulation angle, a second body's velocity, and tire–ground contact. Choose rigid, flexible, or ideal geometric constraints according to the task.



Paired tension forces

Rope tension couples two moving bodies

Connections add states and constraint forces; adding payload mass to one rigid body is insufficient.

4.8.4 Other Vehicles and Model Selection: Resources and Dependencies

Published Examples: Check Tools and Hardware

[installation directory]/RflySimAPIs/4.RflySimModel/2.AdvExps/ • Each example: Readme.pdf			
e3_FWingModelCtrl	Conventional fixed-wing	**e8_Helicopter**	Helicopter
e10_Wing	Flying wing	**e9_USV, e9_UUV**	Surface / underwater
e4_VTOLModelCtrl	Hybrid wing, tail-sitter	**e7_TrailerModelCtrl**	Trailer
e5_CarAckermanCtrl, e6_CarR1DiffCtrl	Ackermann, differential drive	**e2_MultiModelCtrl/ 15.TetheredModelCtrl**	Tethered vehicle

- **Teaching:** 1.BasicExps e2/e5 for fixed-wing, e3/e4 for vehicles; textbook examples are above.
- Section 4.11 permits fixed-wing or ground-vehicle migration. Complex extensions need editable source, libraries, and flight-controller support.

Access to an example does not guarantee editable source, toolboxes, or required hardware.

4.8.4 Other Vehicles and Model Selection: Mechanisms and Validation

Choose Task-Relevant Fidelity and Test Migration

Comparison	Explicit equations	Physical components	Engine contact
Suitable for	Tracing parameters and loads	Mechanical, electrical, and fluid connections	Scene interaction and contact
Example	Kinematics and fixed-wing equation blocks here	Simscape components (textbook Sec. 4.2.2.3)	MuJoCo (optional unit 4.9.2)
Check	Derivations and sign conventions	Component parameters and solver	Contact parameters and integration step

- Low-speed inspection: first check steering and contact. Slung-load swing suppression needs relative motion and tension. Add task-sensitive mechanisms; block count does not measure quality.
- Report reused/replaced/added states, forces, parameters, and interfaces, with calculable predictions and failure conditions. Practice: Section 4.11; independent judgment: Section 4.12.

Useful fidelity retains task-sensitive mechanisms and makes validation possible.

Class Exercises

Practice: Vehicle Kinematics, Lift, and Migration

- **Differential drive:** $b = 0.5$ m, $r_w = 0.1$ m, $\omega_L = 10$ and $\omega_R = 14$ rad/s. Under this chapter's NED convention, find v, r, turn direction, and radius. What changes if you incorrectly use right minus left?
- **Fixed-wing support:** $m = 3$ kg, $S = 0.6$ m², $\rho = 1.225$ kg/m³, $g = 9.8$ m/s². At $V = 12$ and 10 m/s, find dynamic pressure $\overline{q}$ and required C_L.

- **Ackermann:** $L_w = 1.2$ m and right steering $\delta = 20°$. Find radius R_c. For rear-axle speed $v = 1.5$ m/s, what is heading rate r?

- **Migration:** choose a tethered UAV or surface vessel. List added states, forces, and parameters relative to a quadcopter; propose one analytical validation case and one boundary case.

Reference Answers

Set Signs and Validity Conditions Before Substitution

- **Differential drive:** $v_L = 1.0$ and $v_R = 1.4$ m/s, $v = 1.2$ m/s, $r = (v_L - v_R)/b = -0.8$ rad/s. Left turn, radius 1.5 m. Right minus left gives +0.8 and reverses the predicted direction.
- **Lift:** at 12 m/s, $\overline{q} = 88.2$ Pa and $C_L \approx 0.556$; at 10 m/s, 61.25 Pa and 0.80. Reducing speed to 5/6 raises required C_L by a factor of 1.44. Check maximum lift coefficient.
- **Ackermann:** $R_c = L_w / \tan\delta \approx 3.297$ m and $r = v \tan\delta / L_w \approx 0.455$ rad/s. Positive means a right turn.
- **Migration, surface-vessel example:** add submerged volume, buoyancy, and added mass; hydrodynamic damping replaces aerodynamic forces. Validate static draft equilibrium in calm water; use large heel or emergence as a boundary case.

Section Summary

Reuse the Solver; Adapt Loads, Actuators, and Constraints

- **Method:** replace stages along actuator → loads → rigid-body integration → sensors. Predict analytical special cases before comparing on the platform: one-rotor torque, dynamic-pressure lift, differential-drive arcs, and Ackermann radius.

- **Limits:** ideal kinematics assumes low speed and no sideslip. Aerodynamic coefficients have validity ranges; assess stall using maximum lift coefficient. Initial state is not trim; choose complex-model fidelity for the task.
- **Common errors:** NED right turns are positive; differential yaw uses left minus right. Do not directly add isolated-rotor thrusts for a coaxial pair. Normalized input is not wheel speed or steering angle.
  The two fixed-wing templates have different port names/order. Count gravity once.

Predict analytical cases, then compare each stage on the platform; signs and interface order are easiest to get wrong.