Chapter Outline

Unified Fault Modeling Framework

Chapter 7 Health Management and Safety Assessment

7.1 Health Management Fundamentals

7.2 Unified Fault Modeling

7.3 Safety Reinforcement and Fault Data

7.4 Fault Hazards and Safety Assessment

7.5 Diagnosis and Prognostics

7.6 Safety Decisions and Improvement

7.7 Fault Injection Interfaces

7.8 Experiments and Validation

7.9 Exercises and Classroom Discussion

4 Units in This Section

7.2.1 Fault Classification and Unified Representation

Textbook: Sec. 7.1.3.1–7.1.3.3

7.2.2 Propulsion and Payload Faults

Textbook: Sec. 7.1.3.4 (propulsion, structure)

7.2.3 Sensor and Communication Faults

Textbook: Sec. 7.1.3.4 (sensors, links, environment)

7.2.4 Modeling Methods and Healthy References

Textbook: Sec. 7.1.3.3

7.2.1 Fault Classification and Unified Representation: Why Model Faults

Fault Models Define Comparable Abnormal Conditions

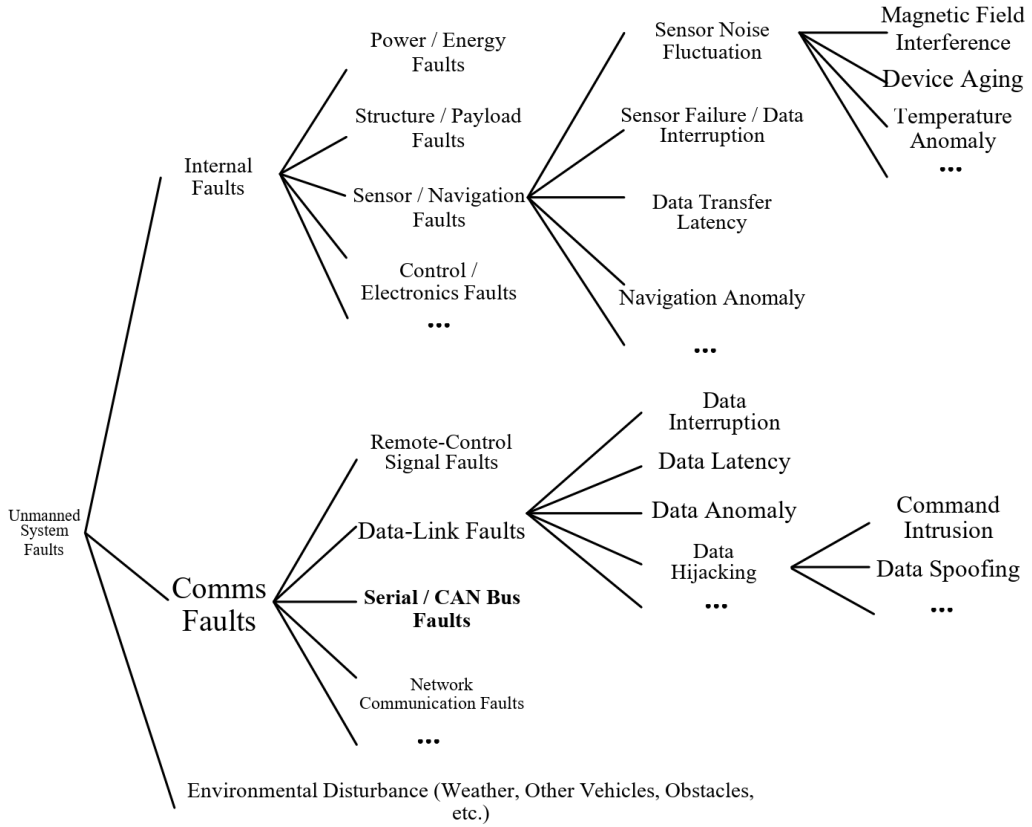
In the same inspection task, propulsion loss, a positioning bias, and link delay may all cause the vehicle to deviate from its flight path.

Element	What to specify	Motor example
Location	Which component or signal changes	Thrust output of rotor 1
Effect	Parameter change, mode switch, added signal	Thrust effectiveness: 1 to 0.6
Trigger / recovery	Time, condition, duration, recovery rule	From 1 s until the example ends
Response	Input, true state, observation changes	Total thrust falls at fixed control input

Repeatable descriptions support comparison; fault probabilities need platform incident data.

7.2.1 Fault Classification and Unified Representation: Classification

Fault Classification Identifies Both Location and Cause



Internal faults: changes in propulsion, sensing, control, structure, or payload.

Communication faults: abnormal transfer between systems or internal interfaces.

Environment: wind, magnetic fields, blockage, weather, and obstacles change conditions.

Location: perception, decision, actuation.
Cause: internal, communication, environment.
Example: magnetic interference → perception.

Fig. 7.3 Fault classification in unmanned systems

7.2.1 Fault Classification and Unified Representation: Internal Faults

Similar Measurement Fluctuations Can Have Different Causes

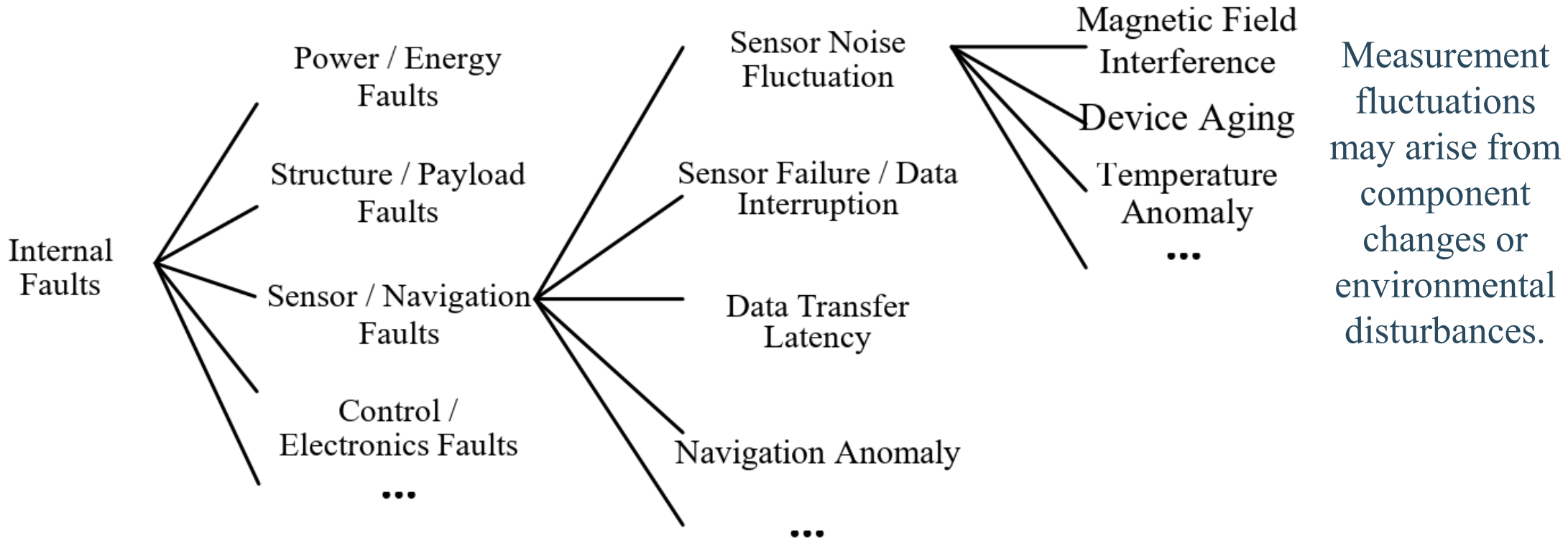
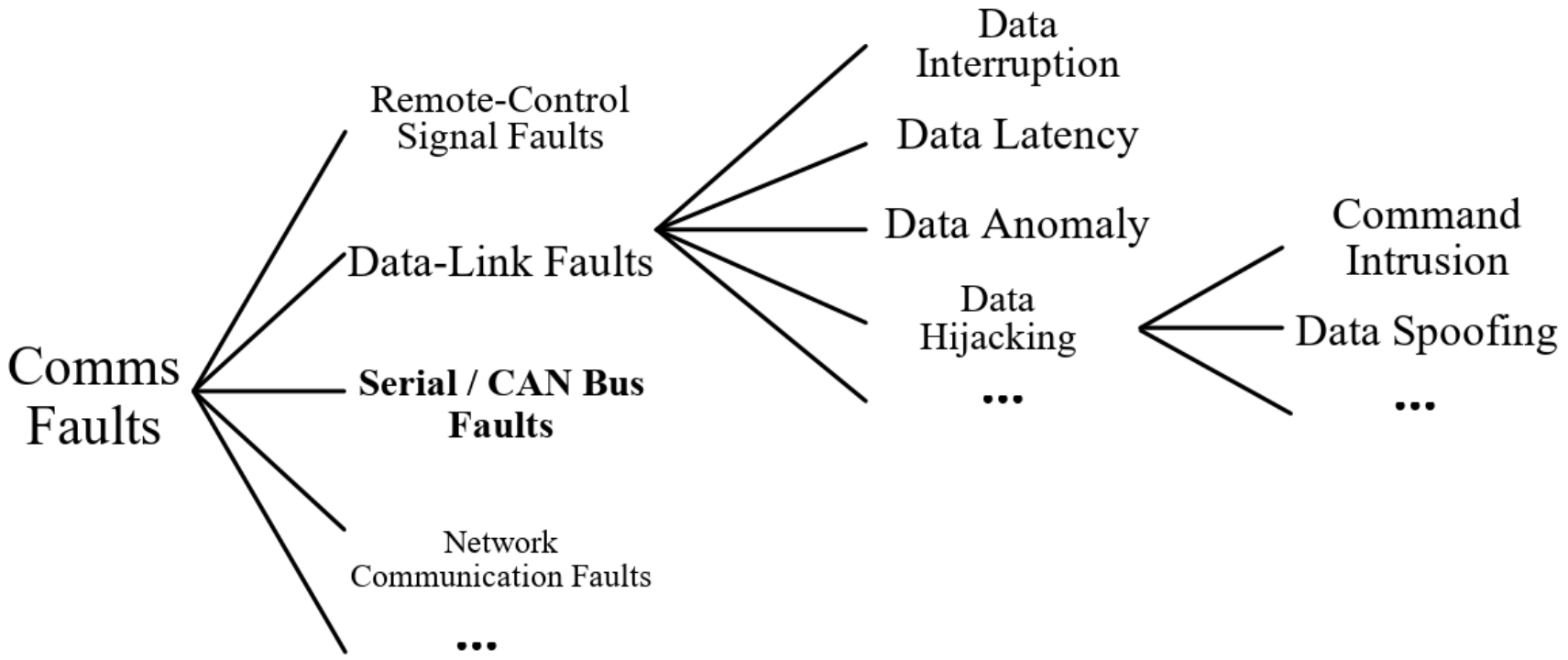


Fig. 7.3, internal faults: Unit 7.2.2, propulsion/structure; 7.2.3, sensors. Control electronics: classification only

7.2.1 Fault Classification and Unified Representation: Communication Faults

Link Faults Affect Information Timeliness or Trustworthiness



Timeliness: interruptions and delay change arrival time.

Trustworthiness: anomalies, hijacking, intrusion, spoofing change content reliability.

Fig. 7.3, communication faults. CAN: controller area network bus

7.2.1 Fault Classification and Unified Representation: Component Fault Models

The Trigger Sets When; the Effect Model Sets What Changes

External trigger
Type, time, condition

→

Internal fault effect
Change parameters/signals

→

Motion / energy model
State and energy anomalies

Form of effect	Change in the model	Minimal example
Parameters	Modify a coefficient or bias	Lower thrust coefficient; higher zero bias
Mode switch	Switch computation/output logic	Normal update to frozen/invalid output
Superposition	Add input, state, or output disturbance	Sinusoidal vibration; random noise

Unify fault descriptions; keep equations specific to each component's physics.

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7.2.4 Modeling Methods and Healthy References

Textbook: Sec. 7.1.3.3

7.2.2 Propulsion and Payload Faults: Thrust Effectiveness

Thrust Effectiveness and Speed Scaling Give Different Losses

Theoretical example: identical propellers and fixed aerodynamic conditions; compare the thrust of one rotor only.

$$F_0 = c_T \omega^2$$

F_0: healthy thrust, N; ω: rotational speed, rad/s.
c_T: thrust coefficient, in $\mathrm{N}/(\mathrm{rad/s})^2$.

$$F_\eta = \eta F_0 = 0.8 \times 5 = 4\ \mathrm{N}$$

η: dimensionless coefficient scaling thrust.

$$F_\alpha = c_T(\alpha\omega)^2 = 0.8^2 \times 5 = 3.2\ \mathrm{N}$$

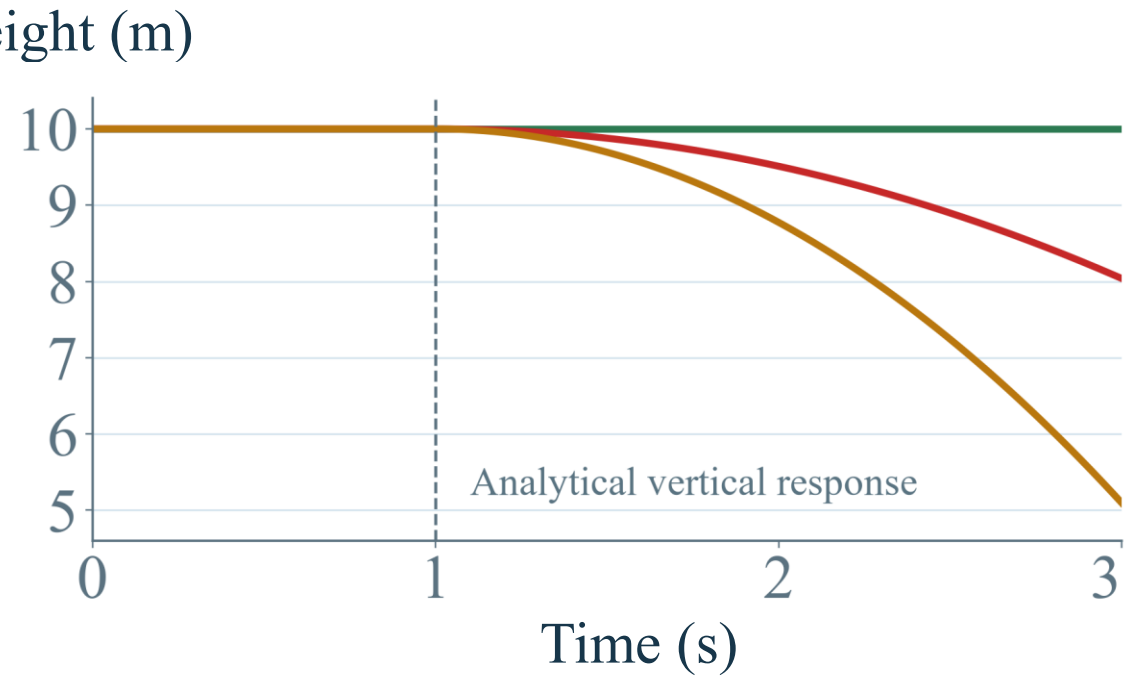
α: dimensionless speed scale. The two 0.8 factors give 20% and 36% thrust loss.

Specify where a parameter acts; a health coefficient alone is insufficient.

7.2.2 Propulsion and Payload Faults: Calculation and Response

Vertical Response to the Loss of One Rotor's Effectiveness

Theory: 2 kg quadrotor; hover at 10 m from rest. Fault at 1 s; hold control inputs fixed.
Healthy thrust 4.905 N/rotor; $g = 9.81\ \mathrm{m/s^2}$. Upward positive; no drag or attitude coupling.



- Healthy: thrust effectiveness 1
- Rotor 1 effectiveness 0.6
- Rotor 1 effectiveness 0

$$F_\Sigma = 4.905 \times 3.6 = 17.658\ \mathrm{N}$$

$$a_z = F_\Sigma/m - g = -0.981\ \mathrm{m/s^2}$$

$$v_z(1.1\ \mathrm{s}) = 0.1a_z = -0.0981\ \mathrm{m/s}$$

$$h(3\ \mathrm{s}) = 10 + 0.5a_z \times 2^2 \approx 8.04\ \mathrm{m}$$

7.2.2 Propulsion and Payload Faults: Structure and Payload

Payload Detachment Changes Mass, Center of Mass, and Inertia

Theory: body 1.6 kg, point payload 0.4 kg at body $x = 0.2$ m; body-center origin.
x_c: combined center of mass; $J_{y,b} = 0.03\ \mathrm{kg\,m^2}$: body-center pitch inertia. Ignore release impulse.

Before detachment: $m = 2$ kg

$$x_c = 0.4 \times 0.2/2 = 0.04\ \mathrm{m}$$

$$J_y = J_{y,b} + 1.6x_c^2 + 0.4(0.2 - x_c)^2$$

$$J_y = 0.0428\ \mathrm{kg\,m^2}$$



After detachment

$$m = 1.6\ \mathrm{kg}, \quad x_c = 0$$

$$J_y = 0.03\ \mathrm{kg\,m^2}$$

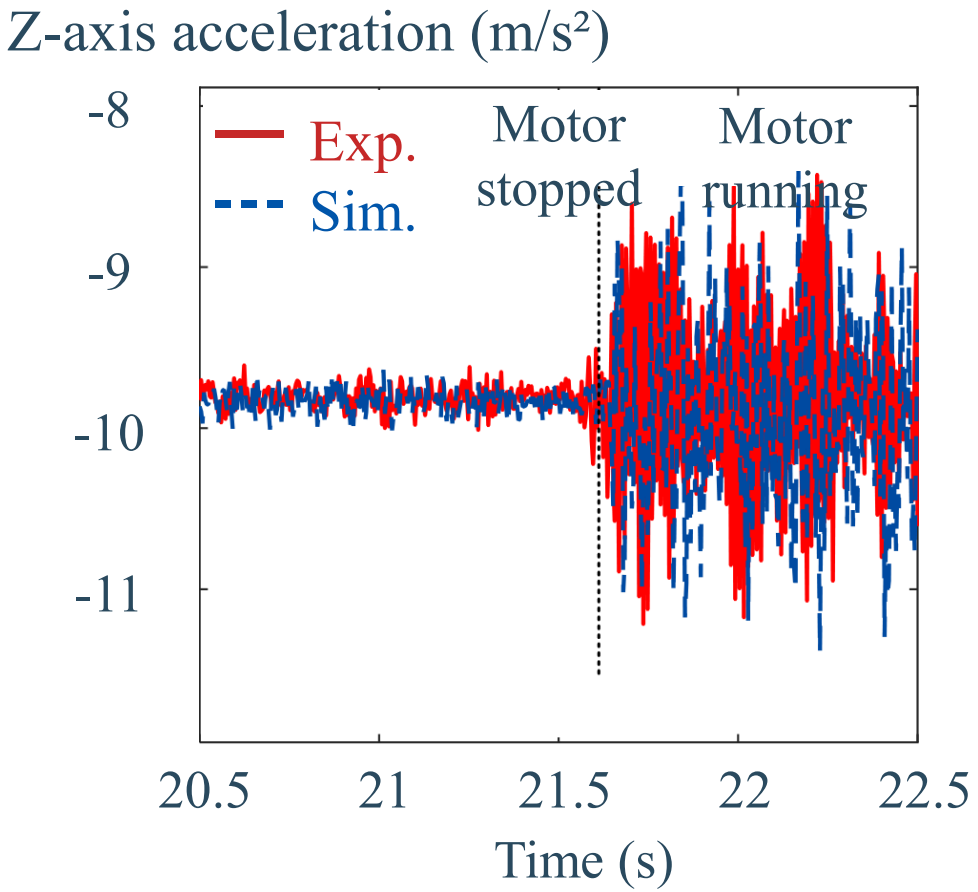
$$a_z = 19.62/1.6 - 9.81$$

$$a_z = 2.4525\ \mathrm{m/s^2}$$

One trigger updates mass, center of mass, and inertia; a step or ramp sets the change rate.
Upward positive; hover thrust stays at 19.62 N instantaneously; $g = 9.81\ \mathrm{m/s^2}$.

7.2.2 Propulsion and Payload Faults: Vibration Evidence in Acceleration

Measurement Fluctuations Increase When the Motor Runs



Observation: Z-axis accelerometer fluctuations increase clearly when the motor runs.

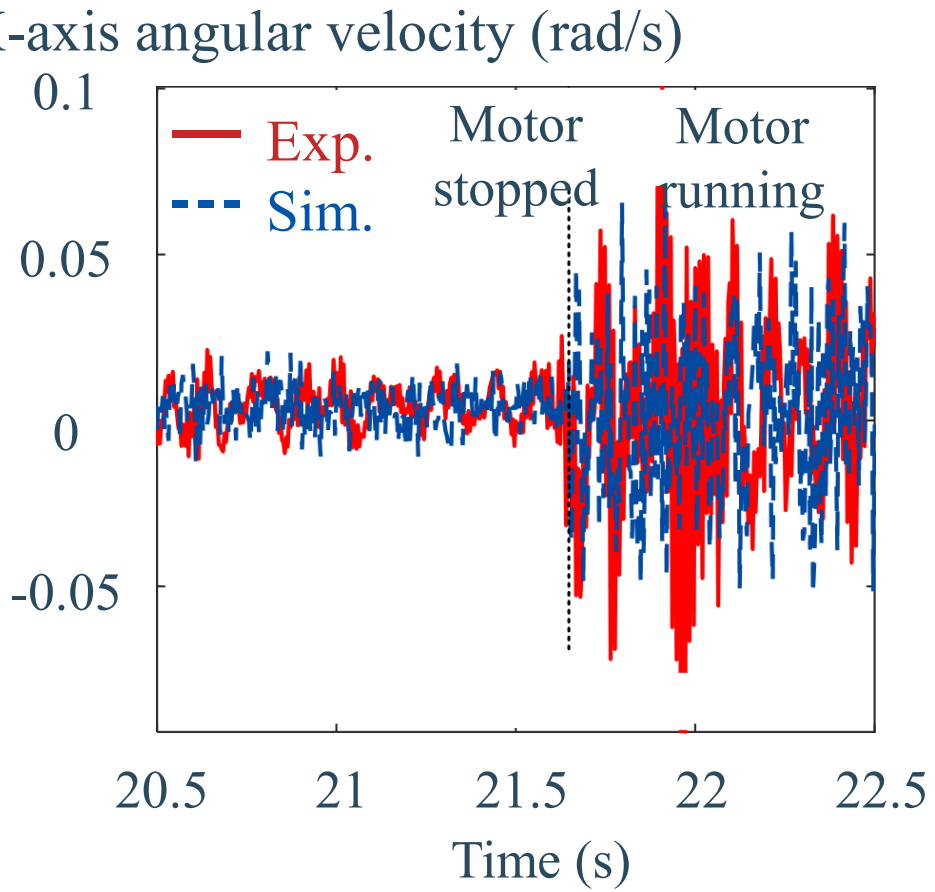
Baseline: about −9.8 m/s² from gravity projection. Vibration is the deviation from the mean.

Model check: mean, variance, spectrum. Align operating conditions and time. Compare random samples statistically.

Fig. 7.4(a) Exp.: experiment; Sim.: simulation
Accelerometer noise from motor vibration

7.2.2 Propulsion and Payload Faults: Vibration Evidence in Angular Rate

Vibration Also Enters the Angular-Rate Measurement Channel



Gyroscope: angular velocity, rad/s.
An inertial measurement unit (IMU) usually contains gyroscopes and accelerometers.

Propagation: motor/structural vibration reaches several channels, causing correlated fluctuations.
Random terms: broadband fluctuations.
Periodic terms: narrowband components.
Fit each channel's mean, variance, spectrum.

Fig. 7.4(b) Exp.: experiment; Sim.: simulation
Gyroscope noise from motor vibration

7.2.2 Propulsion and Payload Faults: Equivalent Signal Models

Periodic and Random Terms Describe Different Vibration Features

Theoretical example: add equivalent vibration to ideal X-axis acceleration. The parameters are classroom inputs.

$$d_a(t) = A\sin(2\pi f t) + \sigma\epsilon(t), \quad \epsilon \sim \mathcal{N}(0,1)$$

Periodic amplitude $A = 0.2\ \mathrm{m/s^2}$; frequency $f = 5$ Hz.
Random standard deviation $\sigma = 0.1\ \mathrm{m/s^2}$; ϵ is a dimensionless standard normal sample.

$$d_a(0.05) = 0.2\sin(\pi/2) + 0.1 \times 1 = 0.3\ \mathrm{m/s^2}$$

After fitting amplitude, check the spectrum and correlations between channels.

7.2.2 Propulsion and Payload Faults: Actual Model Entry Points

The Current Examples Insert Faults into the Motor Signal Chain

API (application programming interface) examples: [installation directory]/RflySimAPIs/7.RflySimPHM/0.ApiExps/

Run: Unit 7.8.2 (Example Entry), 1.BasicExps/e3_MotorFault.

Example folder	Model entry files	What to inspect
e6_UseFaultLib	Init.m; MotorFault.slx Readme.pdf	External trigger and MotorFault block location
e8_BaseMotorFault	Init.m; MulticopterModel.slx Readme.pdf	Fault block connection in the minimal vehicle template

Noise-free branch (no added vibration noise): y(i) = inPWMs(i) * FaultParams(i);

Input command → **Fault coefficient** → **Motor / propeller / dynamics**

This coefficient scales commands; downstream motor dynamics determine speed and thrust.

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Textbook: Sec. 7.1.3.3

7.2.3 Sensor and Communication Faults: Four Sensor Stages

Four Stages Connect the True State to the Measurement

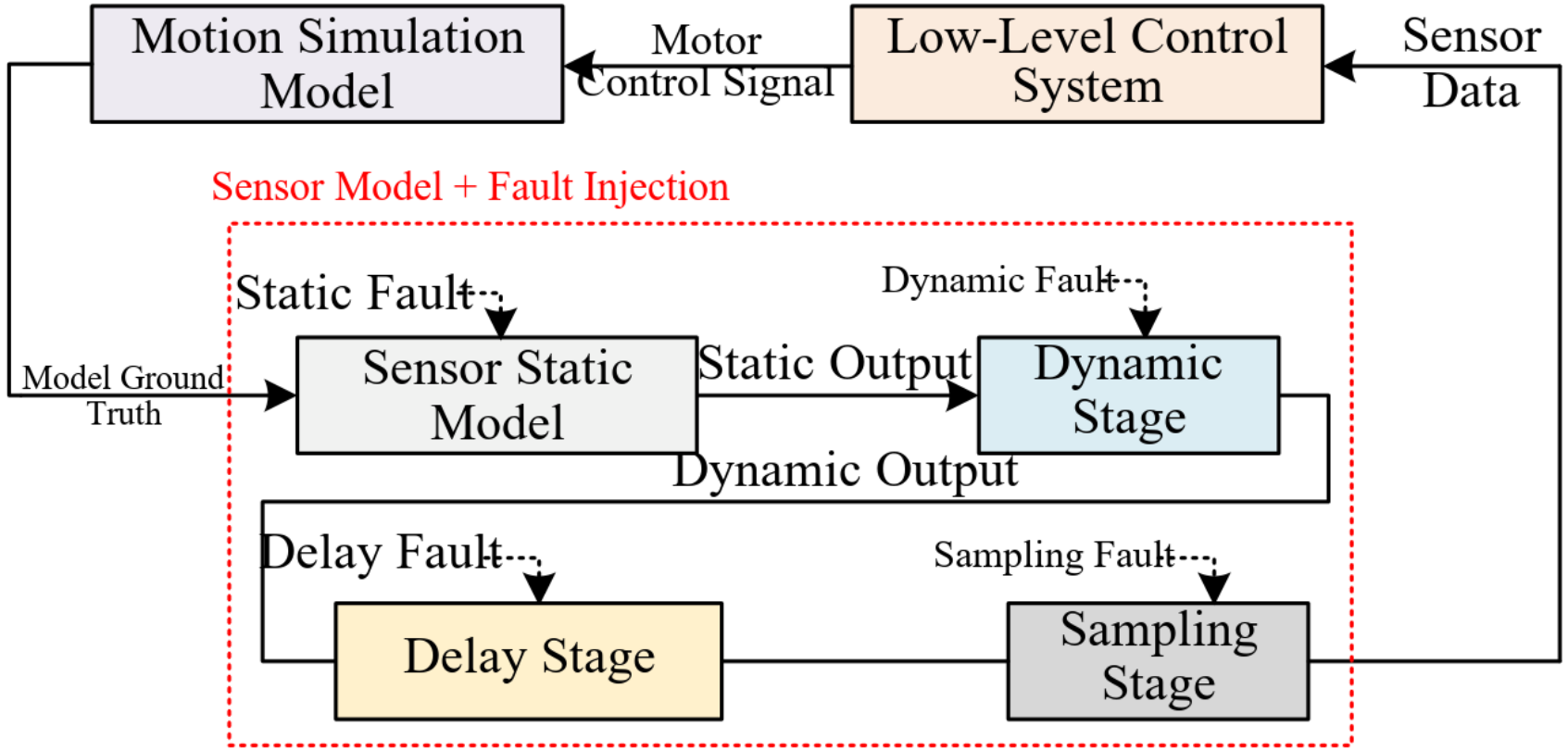


Fig. 7.5 Sensor fault model

Static: scale, bias, calibration

Dynamics: lag or distortion

Delay: read a past state

Sampling: update period and hold

7.2.3 Sensor and Communication Faults: Static and Noise Models

The Separate Effects of Scale, Bias, and Noise

Theoretical example: an X-axis accelerometer, with static effects applied at the measurement output.

$$y = s\,a + b + n, \quad n = \sigma\epsilon, \quad \epsilon \sim \mathcal{N}(0,1)$$

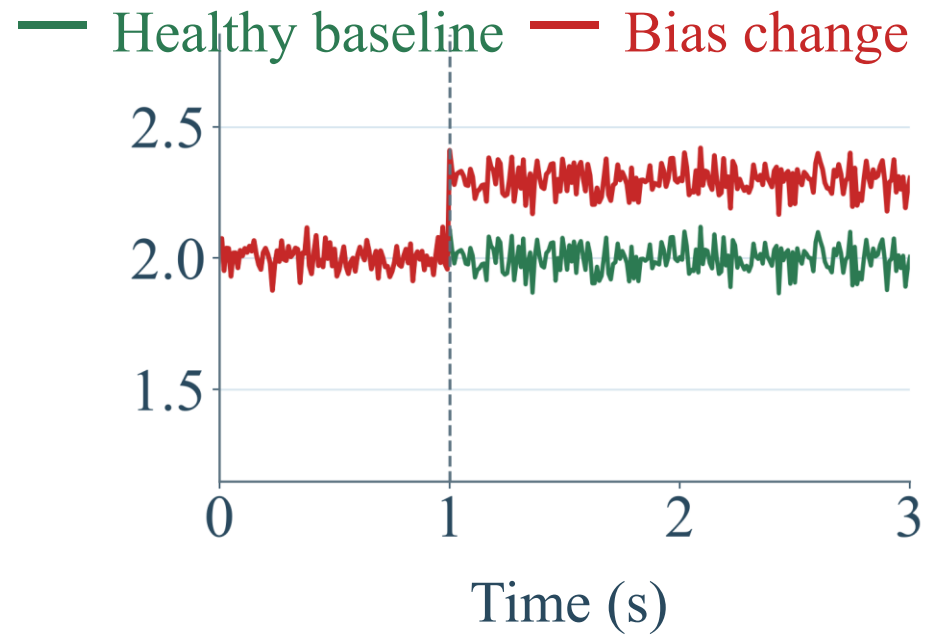
Quantity	Meaning and units	Given value
$a,\ y$	Ideal and measured values, m/s²	Ideal acceleration 2 m/s²
$s,\ b$	Scale: dimensionless; bias: m/s²	Scale 1.05; bias 0.3 m/s²
$n,\ \sigma$	Noise, standard deviation (m/s²)	Current noise sample 0.1 m/s²

$$y = 1.05 \times 2 + 0.3 + 0.1 = 2.5\ \mathrm{m/s^2}$$

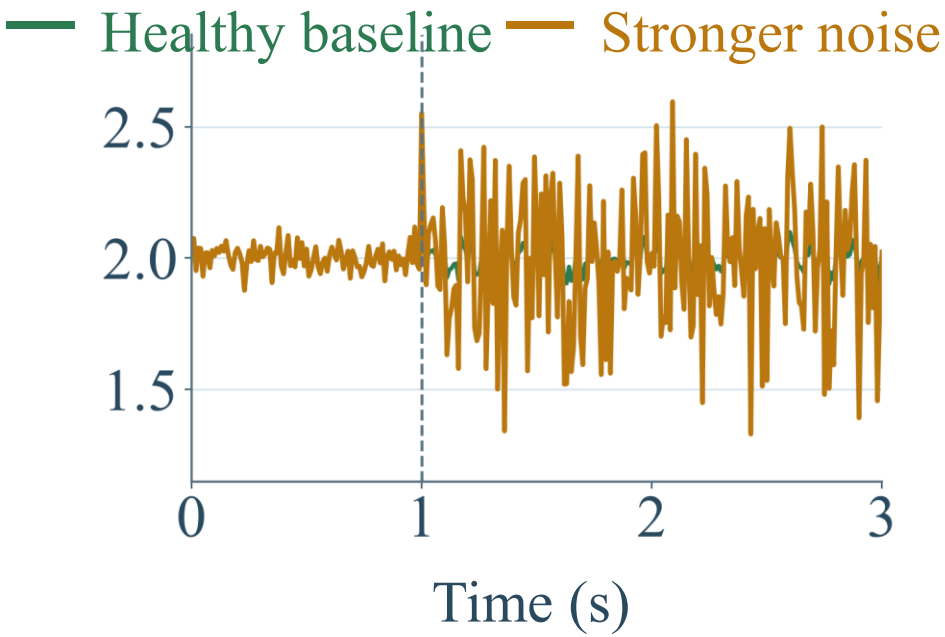
7.2.3 Sensor and Communication Faults: Reading the Response

Bias Shifts the Mean; Noise Increases the Spread

Constant bias: mean shifts upward



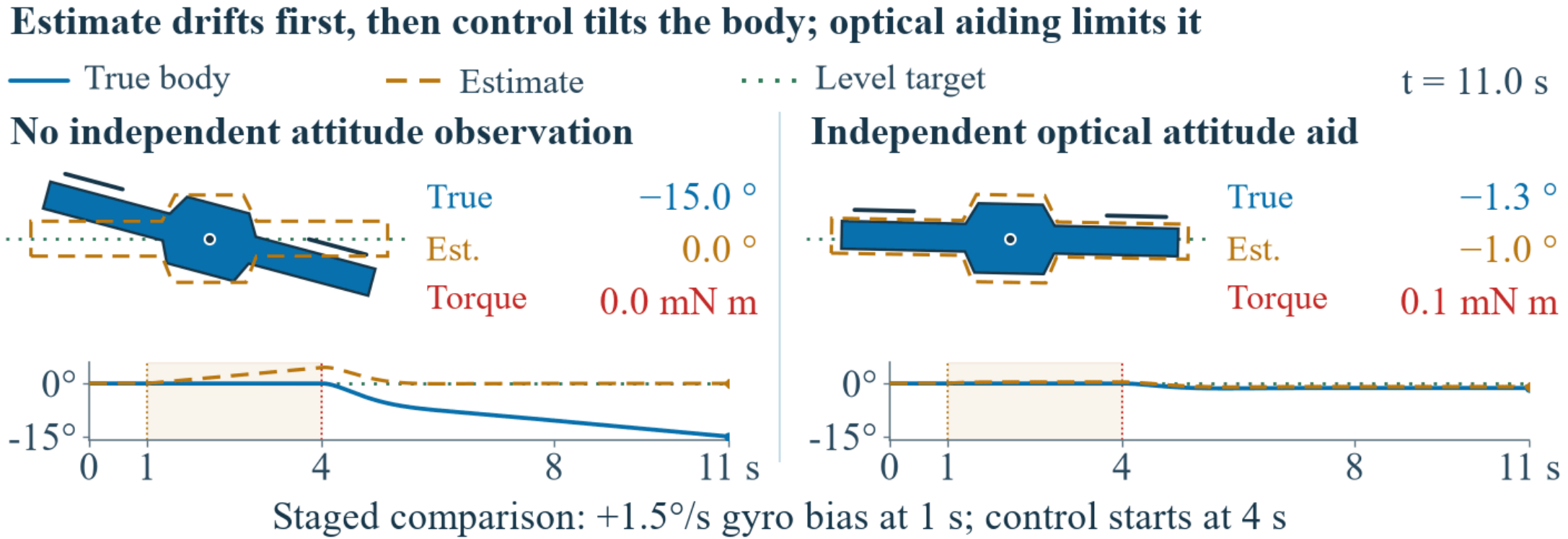
Stronger noise: wider spread



Theoretical model signals: parameters change at 1 s (teaching example).

7.2.3 Sensor and Communication Faults: Inertial Measurement Bias

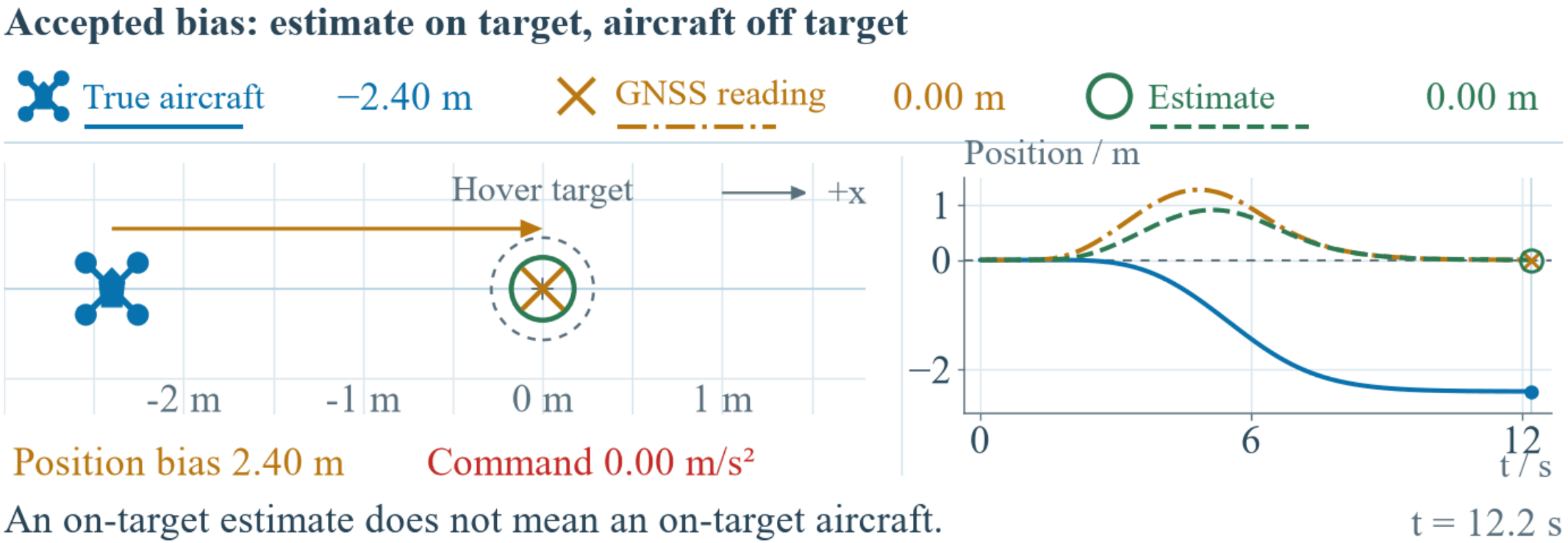
An Attitude Estimate Bias May Make the Controller Tilt the Vehicle



Gyroscope bias changes the attitude estimate; control torque changes true attitude (MuJoCo simulation). Same bias with/without independent optical attitude aiding; staged timing is labeled.

7.2.3 Sensor and Communication Faults: GNSS Position Bias

A Rightward Position Bias May Drive the Vehicle Left



Accepted position bias: apparent rightward error makes control act left (MuJoCo simulation).
Filled: true; cross: global navigation satellite system (GNSS) reading; hollow: estimate. Target fixed.

7.2.3 Sensor and Communication Faults: Timing Calculation

Slow Dynamics, Pure Delay, and Sample-and-Hold Differ

Theoretical u steps from 0 to 1 m/s at 0.25 s; all y start at 0.
Each comparison keeps one timing effect; the dynamic step runs from 0.25 to 0.35 s.

Dynamics
First-order lag

$$\tau\dot{y} + y = u, \quad y_{k+1} = e^{-\Delta t/\tau} y_k + (1 - e^{-\Delta t/\tau}) u_k$$

Time constant τ

$$\tau = 0.2\,\text{s}, \Delta t = 0.1\,\text{s}: \quad y(0.35\,\text{s}) = 1 - e^{-0.5} = 0.393\ \text{m/s}$$

Delay
Pure time lag

$$y_d(t) = u(t - L), \quad L = 0.15\,\text{s}: \text{ first change at } 0.40\,\text{s}$$

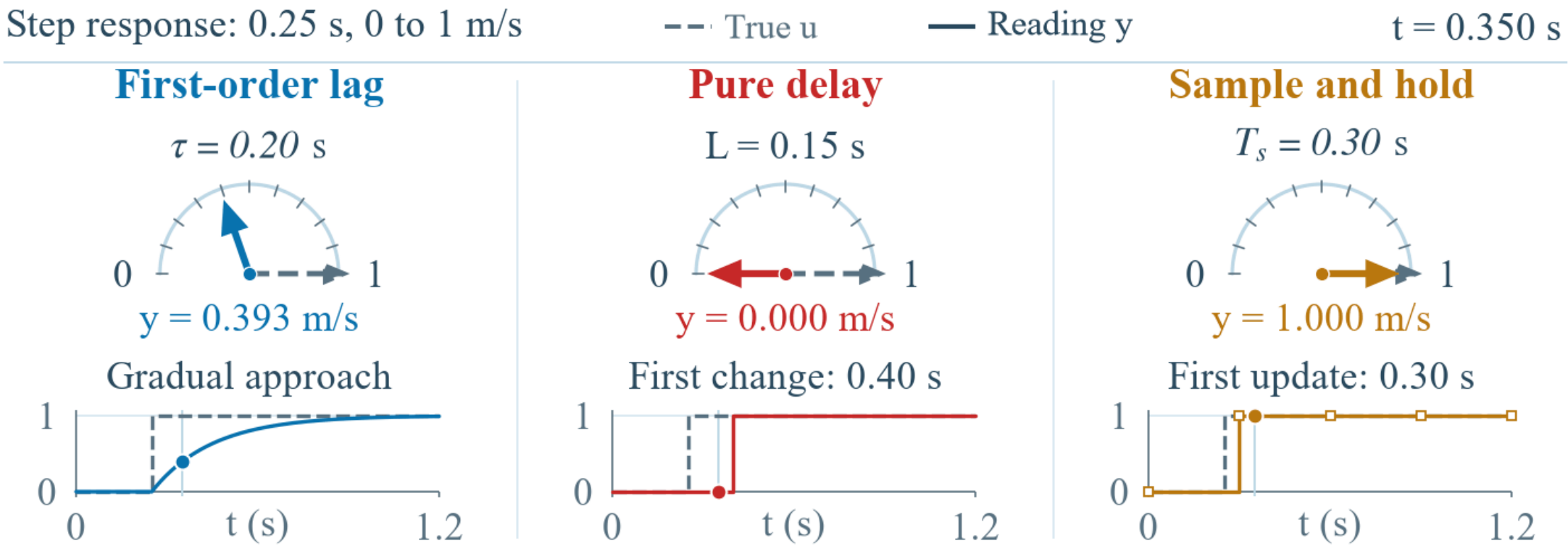
Sampling
Zero-order hold

$$y_h(t) = u(kT_s), \quad kT_s \le t < (k+1)T_s, \quad T_s = 0.30\,\text{s}$$

Period T_s: hold between samples; first update to the new value at 0.30 s.

7.2.3 Sensor and Communication Faults: Timing Responses

Three Timing Responses to the Same Velocity Input



First-order dynamics, pure delay, and sample-and-hold under the same step input (conceptual illustration).

7.2.3 Sensor and Communication Faults: Communication Interruptions

Holding Old Values After Packet Loss Increases Information Age

Theory: send every 0.1 s; hold the last valid command after loss. Reception resumes at 0.4 s. Information age = current time − send time of the data in use.

Time (s)	0	0.1	0.2	0.3	0.4	0.5
Sent speed (m/s)	0	1	2	3	4	5
Packet arrives?	Yes	Yes	No	No	Yes	Yes
Receiver uses	0	1	1	1	4	5

At 0.3 s: $\text{information age} = 0.3 - 0.1 = 0.2\ \text{s}, \quad \text{command difference} = 3 - 1 = 2\ \text{m/s}$

Hold, zero, or invalid flag: effects differ. Specify the interruption window and recovery policy.

7.2.3 Sensor and Communication Faults: Other Communication Faults

Bit Errors, Reordering, and Interference Affect Different Features

Three communication-fault classes: specify effects, model parameters, and test objectives.

Link interruption

Effect: block uplink/downlink commands and state feedback in a time window.
Parameters: window start/end, single/intermittent loss, recovery policy.
Test: hold last command, lost-link failsafe, hover, return to launch.

Bit errors and garbling

Effect: random bit flips, packet loss, duplicates, reordering; zero/out-of-range/illegal field encoding.
Parameters: bit/packet error rates, duplicate probability, reorder window, field rules.
Test: parsing, fault tolerance.

Interference and attacks

Sources: congestion, electromagnetic interference, scanning/flooding/replay attacks.
Parameters: random/burst delay, jitter, bandwidth/packet loss; intensity over time and spectrum.
Test: interference resistance, robustness.

7.2.3 Sensor and Communication Faults: Environmental Disturbances

Environmental Disturbances Act Through Forces or Measurements

Wind in space/time Relative wind	→ Aerodynamic force and torque	→ Motion and control response
Magnetic anomaly / satellite blockage	→ Magnetometer / position measurements change	→ Estimation and control response change

$$F_x = 2\ \text{N},\ m = 2\ \text{kg}: \quad a_x = F_x/m = 1\ \text{m/s}^2$$

$$\Delta v_x = a_x \Delta t = 1 \times 0.1 = 0.1\ \text{m/s}$$

Theory: given equivalent wind force, no control compensation. Actual wind speed needs an aerodynamic force model.

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Textbook: Sec. 7.1.3.3

7.2.4 Modeling Methods and Healthy References: Method Comparison

Physics-Based, Data-Driven, and Hybrid Modeling

Method	Model source	Representation and tradeoffs
Physics-based modeling	Physical parameters, structure, control logic	Explains force/mass/inertia propagation; unknown structure or inaccurate parameters limit accuracy.
Data / signal modeling	Logs, calibration tables, vibration or response data	Lookup tables, regression, noise distributions; range depends on conditions and data quality.
Hybrid modeling	Physical baseline plus fitted correction	Preserves propagation, corrects mismatch; specify interfaces and data use for both parts.

Superposition: how a fault acts. Physics/data methods: how the model is obtained.

7.2.4 Modeling Methods and Healthy References: Data-Model Calculation

Lookup Tables Interpolate Between Adjacent Data Points

Theoretical example: a teaching table for one fixed fault condition, with linear interpolation from rotational speed to thrust.

Speed (rad/s)	300	400	500
Given thrust (N)	0.630	1.120	1.750

$$F(450) = 1.120 + \frac{450 - 400}{500 - 400}(1.750 - 1.120) = 1.435\ \text{N}$$

Input sequence	300	350	400	450	500
Thrust (N)	0.630	0.875	1.120	1.435	1.750

Quadratic table: interpolation at 450 is 0.0175 N high; sparser tables increase error.

7.2.4 Modeling Methods and Healthy References: Modeling versus Diagnosis

Fault Models, Healthy References, and Diagnosis Have Different Roles

Main input	Object	Main output
Preset type, coefficient, and trigger conditions	**Fault-effect model**	Changed force, parameters, or measurements
Control input, conditions, and healthy parameters	**Healthy reference model**	Expected healthy response under the same conditions
Observations, reference differences, other evidence	**Diagnostic algorithm**	Anomaly decision, class, or parameter estimate

Example: the model sets $\eta = 0.6$. Independent observations must test whether the diagnostic algorithm detects, locates, and estimates this loss.

7.2.4 Modeling Methods and Healthy References: Enhanced Digital Twin

Learning Healthy Reference Error from Virtual and Real Data

Digital twin (DT): a digital counterpart using physics-based models and real-vehicle data.
UAV: unmanned aerial vehicle.

1 Quantify differences

Same input and conditions: align real observations with model output X_{virt}.

2 Learn the error

Real data − model: learn condition-dependent error-sequence features.

3 Reconstruct / correct

Add reconstructed error $\hat{\Delta}$ to the model output to correct reference X_{comp}.

$$X_{\text{comp}} = X_{\text{virt}} + \hat{\Delta}$$

Adapted from Fig. 1(b): Tu, Nian, Dai. IEEE TAES, 2026, 62: 2460–2476.
Physics-Aware Multichannel Vector Quantization for Hybrid Digital Twin Modeling of UAV Systems

https://doi.org/10.1109/TAES.2025.3639005
Folder: [installation directory]/RflySimAPIs/PaperRes/7.Enhanced-DT/ (paper and Readme.pdf)
Use real observations to learn model error; reference correction is not known-fault injection.

7.2.4 Modeling Methods and Healthy References: Reference Calculation

Residuals Also Contain Healthy-Model Error

Theory: same input and velocity channel. Healthy baseline 2.0 m/s; model reference 1.7 m/s. Healthy paired data give a 0.3 m/s correction; a separate observation is 1.8 m/s.

$$\hat{y}_{\text{healthy}} = 1.7 + 0.3 = 2.0 \ \text{m/s}$$

$$r_{\text{raw}} = 1.8 - 1.7 = +0.1 \ \text{m/s}$$

$$r_{\text{comp}} = 1.8 - 2.0 = -0.2 \ \text{m/s}$$

Residual = observation − reference. Fix sign and units; diagnose with conditions, noise, and multisource evidence.

Source: preceding paper, Tu et al., IEEE TAES (2026). Classroom values.

7.2.4 Modeling Methods and Healthy References: Model Handoff

Reproducible Fault Descriptions Include Timing and a Baseline

Description item	Complete values for the running example
Object / effect	Rotor 1 thrust; dimensionless multiplicative thrust-effectiveness coefficient
Parameter / timing	Changes from 1 to 0.6 at 1 s; ends at 3 s, with no automatic recovery
Healthy baseline	Mass 2 kg, initial height 10 m, zero velocity, same control inputs
Expected / observed	Frozen control: total thrust 17.658 N. Record true state, measurements, control inputs.
Model limits	Vertical translation only; check attitude, compensation, and parameter location in closed loop.

A model, trigger, and observation criteria make injection outcomes verifiable.

Exercises and Discussion

Calculate Parameter Effects and Observation Differences

1 Propulsion parameters: healthy thrust is 6 N. If a factor of 0.7 acts on thrust or rotational speed, what are the output and loss in each case?

2 Communication: send every 0.1 s. The 0.2 s packet (1.5 m/s) arrives; the 0.3 s and 0.4 s packets are lost.
At 0.45 s, what value is still held and what is its information age? Neglect transmission delay.

3 Model and diagnosis: is setting motor effectiveness to 0.7 already a diagnostic result?
Reference 2.5 m/s, correction −0.2 m/s, observation 2.4 m/s: find raw and corrected residuals.

Self-check: show substitutions, units, timing, and which value is preset.

Reference Answers

Distinguishing Fault Effects, Information, and Inference

$$F_\eta = 0.7 \times 6 = 4.2\ \text{N}, \quad F_\alpha = 0.7^2 \times 6 = 2.94\ \text{N}$$

1 Thrust scaling: 30% loss. Speed scaling through the square law: 51% loss. Location determines the loss.

$$u_{\text{used}} = 1.5\ \text{m/s}, \quad \text{information age} = 0.45 - 0.2 = 0.25\ \text{s}$$

2 Age starts at the last valid packet's send time, 0.2 s, and grows until a new packet arrives.

$$r_{\text{raw}} = 2.4 - 2.5 = -0.1\ \text{m/s}, \quad r_{\text{comp}} = 2.4 - 2.3 = +0.1\ \text{m/s}$$

3 Preset 0.7 is not diagnosis; infer from observations. Correction reverses the residual sign.

Exercises and Discussion

Calculate Timing and Payload Changes

4 Timing: first-order lag $\tau = 0.25$ s; input steps from 0 to 1 m/s at 0 s, output initially 0. Use exact discretization for one step $\Delta t = 0.1$ s. Find the output, then compare with pure delay $L = 0.15$ s.

5 Detachment: body 1.5 kg, own pitch inertia 0.03 kg·m²; point payload 0.5 kg at body $x = 0.3$ m. Find combined center of mass x_c and total pitch inertia J_y before detachment. If hover thrust is instantaneously unchanged, find acceleration after detachment. Use $g = 9.81\ \mathrm{m/s^2}$; upward positive.

Self-check: show substitutions, units, positive direction, and parallel-axis distances.

Reference Answers

Checking Discretization, Parallel-Axis Distances, and Signs

$$y(0.1\ \mathrm{s}) = 1 - e^{-0.1/0.25} = 1 - e^{-0.4} = 0.330\ \ \mathrm{m/s}$$

4 Exact discrete coefficient: $e^{-\Delta t/\tau}$. One step reaches 33% of the final value; pure-delay output at 0.1 s is 0.

$$x_c = 0.5 \times 0.3/2.0 = 0.075\ \mathrm{m}$$

$$J_y = 0.03 + 1.5 \times 0.075^2 + 0.5 \times 0.225^2 \approx 0.0638\ \mathrm{kg\,m^2}$$

$$a_z = 19.62/1.5 - 9.81 = 3.27\ \ \mathrm{m/s^2}$$

5 Parallel-axis distances: body 0.075 m, payload 0.3−0.075 = 0.225 m; exact inertia 0.06375 kg·m². After detachment: mass 1.5 kg, center at origin, inertia 0.03 kg·m²; unchanged thrust gives upward acceleration.

Section Summary

Fault Models Need Explainable, Verifiable Effects

Unified description: object, effect, parameter units, trigger, recovery.
Add a healthy baseline and expected response to complete the model.

Methods: physics explains propagation, data fit responses; hybrid models use data to correct physical-model mismatch.

Keep command, speed, and thrust coefficients distinct. Bias, noise, dynamics, and timing alter different features. Interruptions affect arrival; errors/reordering affect content/order; interference affects delay/bandwidth.

Preset parameters define test conditions; healthy references define the normal response. Diagnosis uses observations and must not read fault settings.

The model defines the fault effect; Section 7.7 triggers it and checks the actual response.