Chapter Outline

External Control Principles and Control Modes

Chapter 6
External Control and Trajectory Planning

6.1 External Control Fundamentals

6.2 Control Principles and Modes

6.3 Trajectory Models and Generation

6.4 Planning and Obstacle Avoidance

6.5 Tracking and Aggressive Flight Control

6.6 Frontier Control Technologies

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6.2.2 Ground Control Mode
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6.2.4 Comparison on a Common Task
Textbook: Secs. 6.1.2.1–6.1.2.3

Section Introduction: Three Command Sources

Who Supplies the Next Motion Target?

Method	Input to the Flight Controller	Who Continuously Decides Next?
Remote control	Sticks and mode switches; current mode maps the inputs	Operator observes motion and adjusts inputs continuously
Mission mode	Waypoints and task actions, uploaded and stored onboard	Onboard mission executor advances through mission items
Offboard control	Continuously valid targets: position, velocity, attitude, etc.	External program computes from task and new observations continuously.

Control mode assigns ongoing decisions and abnormal-condition takeover responsibilities.

6.2.1 Remote Control Mode: Controller Channels

Four Channels Together Change Vehicle Motion

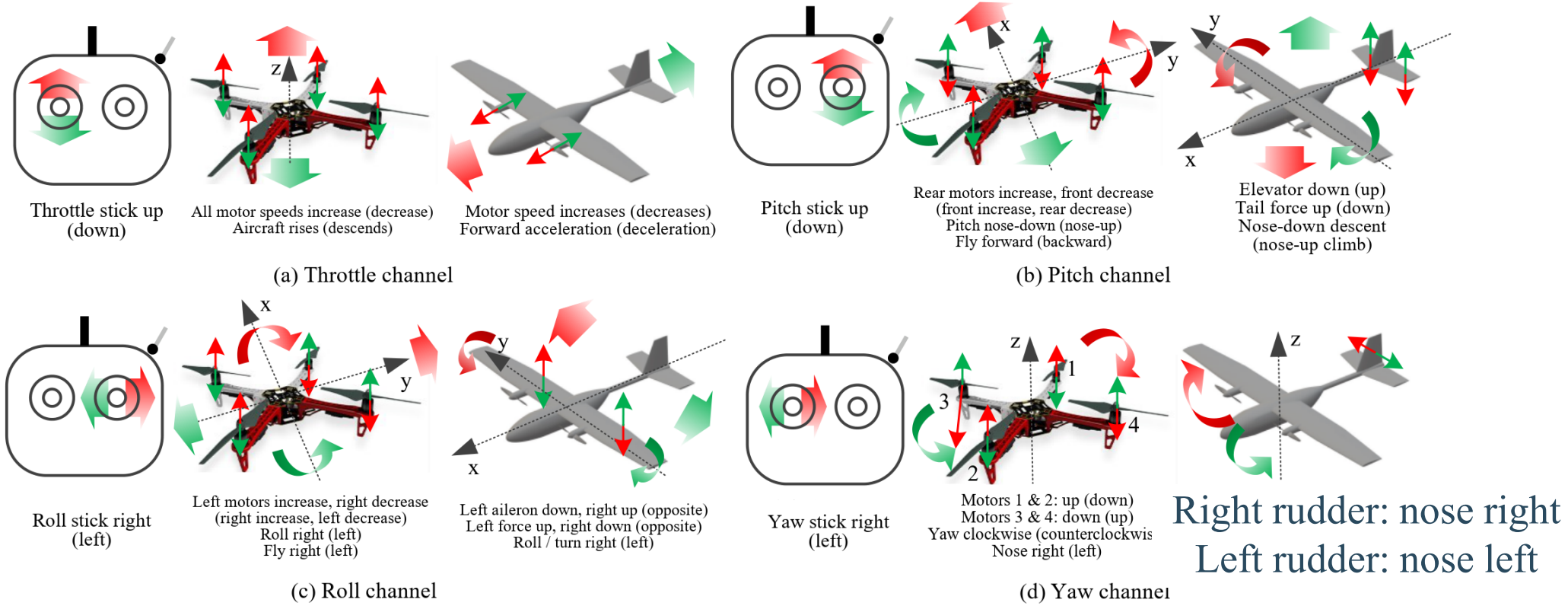
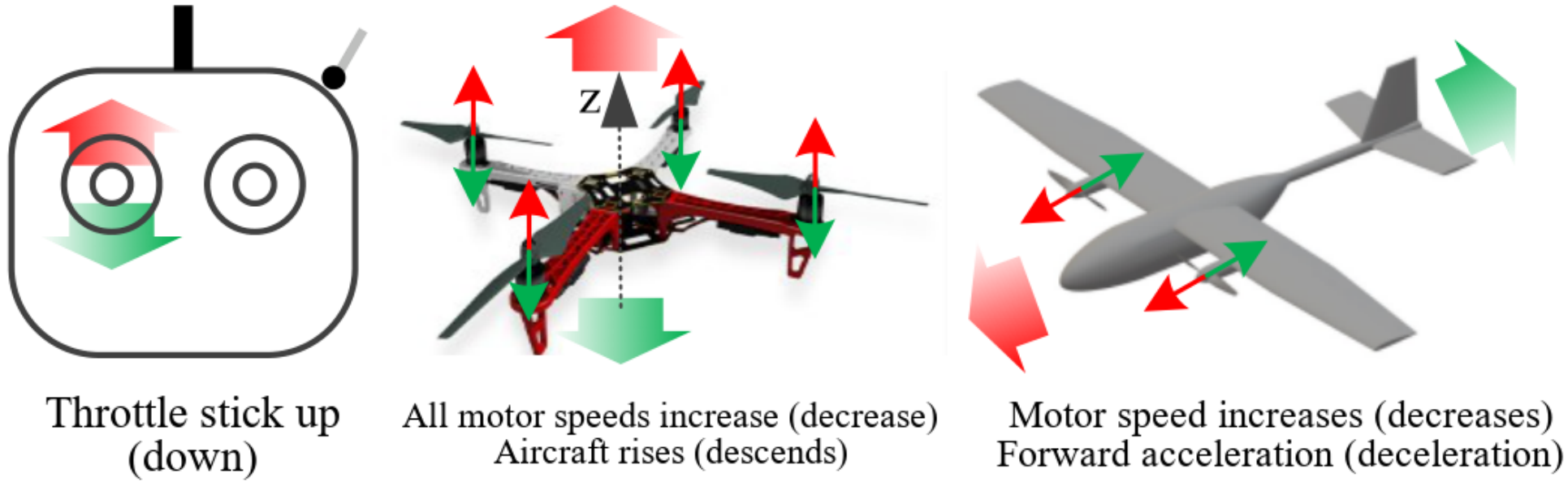


Figure 6.3 Remote Control Channels (the four panels are enlarged next)

6.2 Control Principles and Modes

6.2.1 Remote Control Mode: Throttle Channel

Throttle Requests Total Thrust; the Flight Controller Allocates Motor Outputs

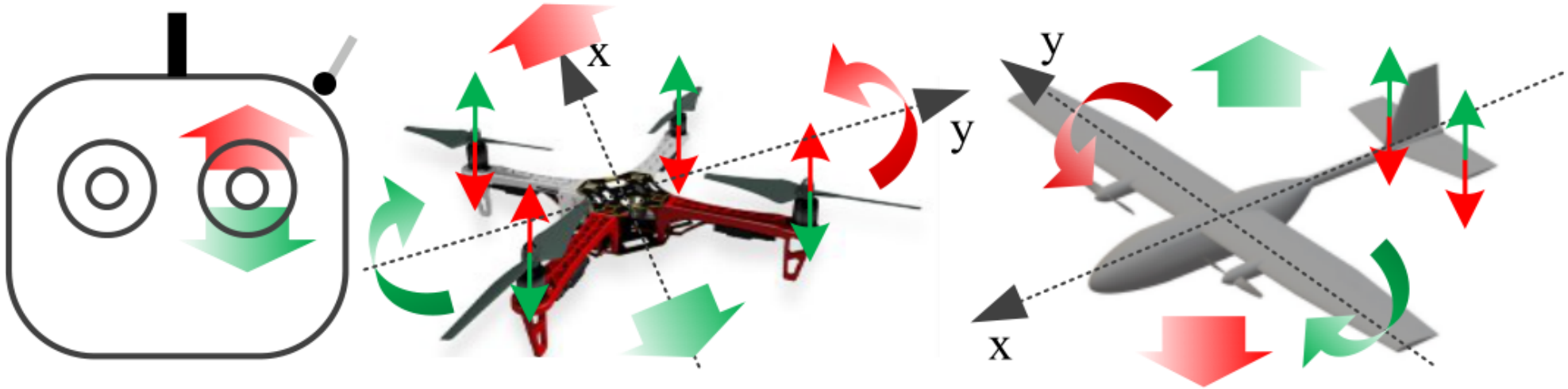


(a) Throttle channel

Figure 6.3(a) Throttle: multicopter total thrust; fixed-wing mainly thrust and airspeed.

6.2.1 Remote Control Mode: Pitch Channel

Pitch Changes Tilt and the Direction of Force

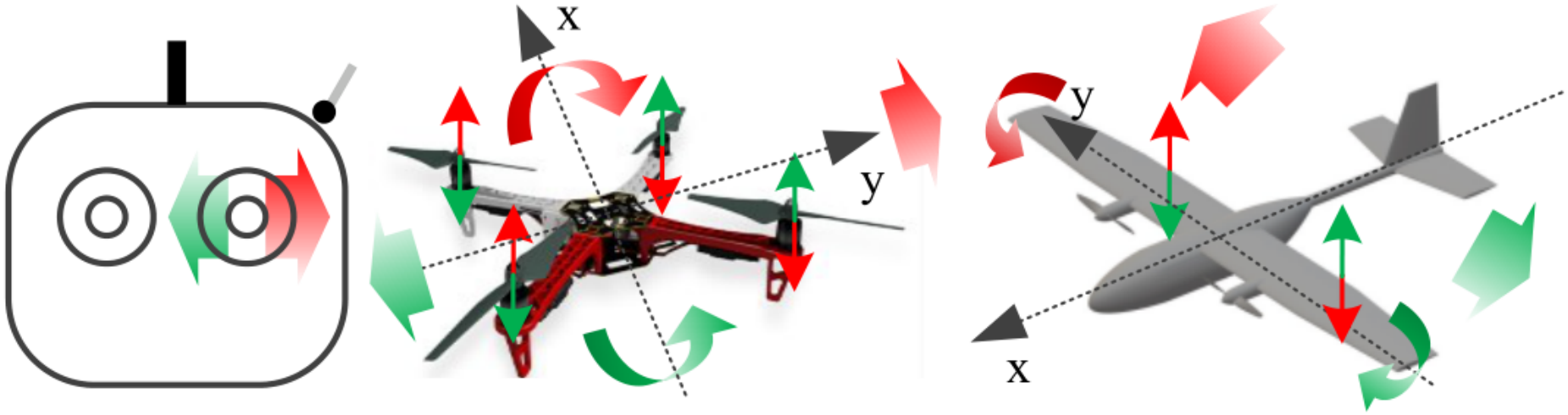


(b) Pitch channel

Figure 6.3(b) Pitch: tilt targets in attitude mode; ground/surface vehicles usually lack pitch control.

6.2.1 Remote Control Mode: Roll Channel

Roll Tilts the Vehicle to Produce Lateral Motion

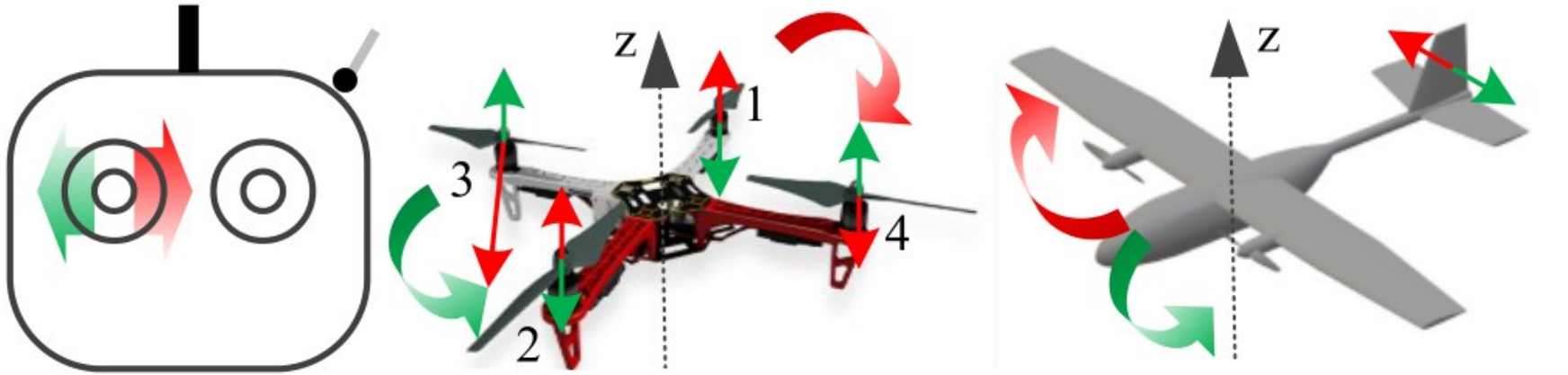


(c) Roll channel

Figure 6.3(c) Roll: tilting first changes force, then motion

6.2.1 Remote Control Mode: Yaw Channel

Yaw Changes Heading; Fixed-Wing Turns Also Rely on Roll



(d) Yaw channel

Figure 6.3(d) Yaw: sticks usually set yaw rate; rotor directions follow the actual configuration.

6.2.1 Remote Control Mode: Multicopter Modes

One Stick Has Different Meanings in Three Modes

Mode	Main Stick Meaning	Holding After Centering	Estimates needed
Stabilized	Tilt + yaw rate; throttle: total thrust	Levels attitude; no altitude/position hold	Attitude estimate; manual input
Altitude	Tilt + yaw rate; throttle: climb rate	Holds altitude; horizontal drift possible	Valid attitude and altitude estimates
Position	Horizontal acceleration/velocity; throttle: vertical velocity	Brakes/holds position; centered throttle: altitude hold	Horizontal position; altitude estimate

Bundled default: PX4 v1.12.3; confirm it in 5.5, “Control Outputs Across Versions.”
Position mode defaults to acceleration mapping; MPC_POS_MODE selects the mapping.
Stabilized/Altitude need no satellite positioning; Position needs valid positioning.

6.2.1 Remote Control Mode: Vehicle Differences

Fixed-Wing Track Holding Requires Forward Flight

Mode	What the Flight Controller Holds	Operation and Constraints
Stabilized	Roll and pitch attitude; no guaranteed position hold	Throttle directly requests thrust; maintain sufficient flight airspeed
Altitude	Altitude; airspeed with a suitable airspeed input	Ground track may drift in crosswind; pitch input changes altitude demand
Position	Altitude, ground track, and supported airspeed control	Forward flight continues; roll turns; yaw coordinates

The same mode name identifies a control task; vehicle motion constraints still apply.

6.2.1 Remote Control Mode: Other Modes

A Mode Switch Can Also Trigger an Autonomous Task

Mode Group	Input or Trigger	Execution
Acro	Continuous angular-rate and thrust requests	For rapid rolls and maneuvers; no automatic position hold
Takeoff / Land / Return	Mode switch / ground station → Takeoff / Land / Return	Flight controller executes it; Return/Land have entry conditions
Follow Me / Orbit / Hold	Ground station / mode switch → Follow Me / Orbit / Hold	Follow a target, orbit, or wait; Hold behavior depends on vehicle

Mode changes set authority and input meaning; the flight controller then produces motion.

6.2.1 Remote Control Mode: Reading the Simulation Example

SendRCPwms Updates Remote-Control Channels

[installation directory]/RflySimAPIs/6.RflySimExtCtrl/0.ApiExps/
e4_PX4RcCtrlAPITest/: Readme.pdf, PX4RcCtrlAPITest.py

```
pwms[2] = 1900
mav.SendRCPwms(pwms)
```

Input: pwms[2] is channel 3 (throttle); 1100→1900 μs, sent by a background loop.

Expected: climb continuously for about 60 s after arming; check that channel value, mode and altitude agree.

Side effects: requests arming (enables motor output; see 5.6, “Controller Overview”). initRCSendLoop sets NAV_RCL_ACT and NAV_DLL_ACT to 0, disabling remote-control (RC) and data-link-loss failsafes.

Ending gap: stops after 60 s without landing; first land under control and confirm disarming.

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6.2.2 Ground Control Mode: Mission Workflow

After Upload, the Onboard Executor Advances the Mission



Mission mode (textbook: Ground Control Mode): plan and upload at the ground station; execute onboard.
A ground-computer program that keeps sending targets uses Offboard control.

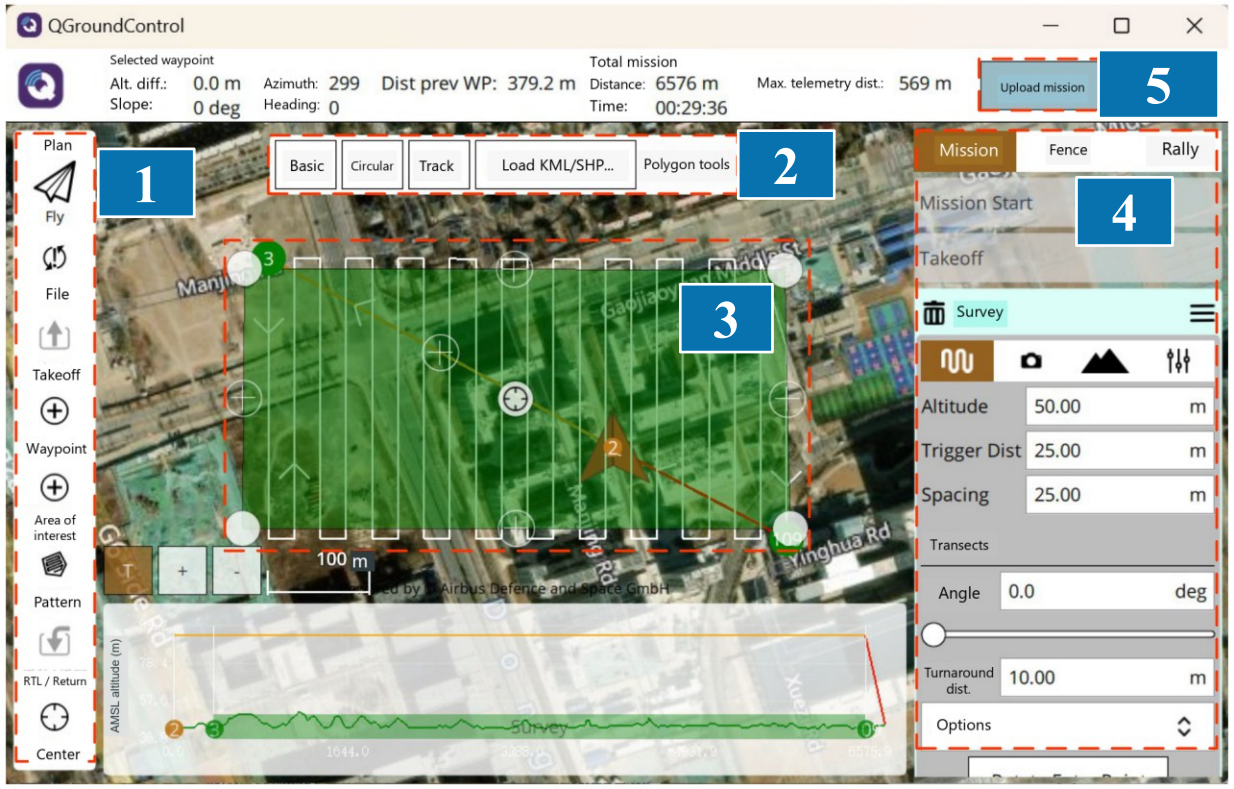
Ground station: edit/upload missions; display position, progress and alerts.

Flight controller: generate motion targets from mission items and advance using state feedback.

Interrupt/resume: after a pause, mode change or mission-item reset, reconfirm the current execution point.

6.2.2 Ground Control Mode: Ground-Station Planning

From an Area to Mission Items and Upload



1–2: mission toolbar and templates.

3: route preview—check coverage and turns.

4: mission-item editing—altitude and actions.

5: upload—send the mission to the vehicle.

Mission list: after upload, awaiting start.

Figure 6.4 QGroundControl mission planning (markers 1–5 explained at right)

6.2.2 Ground Control Mode: Mission Parameters

Trigger Distance and Line Spacing Are Different Parameters



Figure 6.4 (detail) Back-and-forth survey lines

Trigger: along track; line spacing: across track.

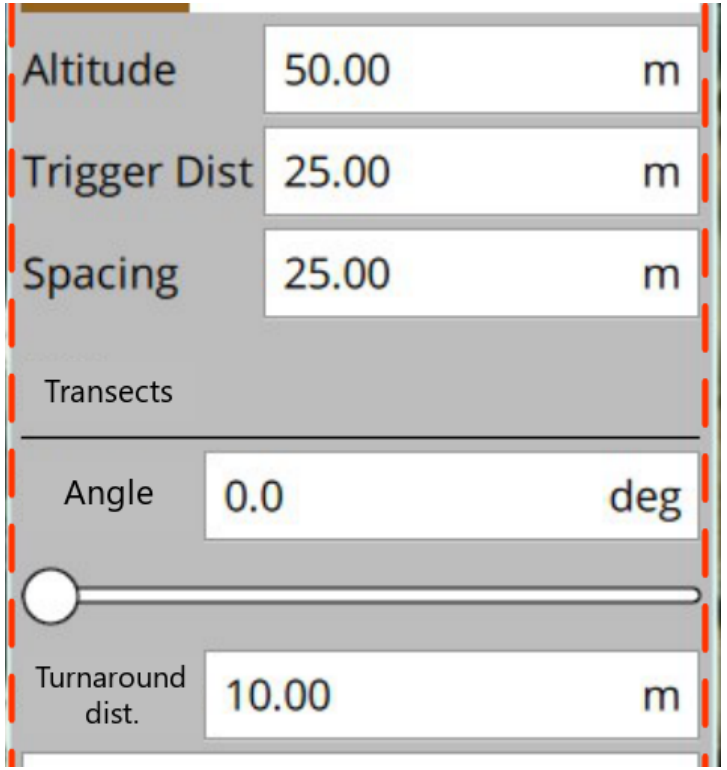


Figure 6.4 (detail) Parameter editing

6.2.2 Ground Control Mode: Waypoints and Actions

Waypoints Specify Where; Mission Commands Specify What to Do

Mission items	Common Mission Commands	Inspection Role
Navigation	NAV_TAKEOFF NAV_WAYPOINT / NAV_LAND	Take off; reach set positions; land at the planned location.
Payload actions	DO_MOUNT_CONTROL DO_SET_CAM_TRIGG_DIST	Adjust the gimbal; trigger photos by travel distance.
Speed and sequence	DO_CHANGE_SPEED DO_JUMP	Change speed; repeat or jump between mission items.

Default speed, heading policy and wait conditions are global; loops need an explicit exit.

6.2.2 Ground Control Mode: Mission Upload

Upload Acceptance, Execution Start, and Completion Are Separate

Declare item count → **Request and transfer items** → **Acknowledge reception** → **Store onboard; await execution**

Observed State	What It Establishes	What Remains?
Upload accepted	Onboard system accepted this mission list	Confirm execution conditions; start the mission
Current item advances	Mission executor running	Confirm actions, path and final state
Last item complete	Mission-list end condition met	Confirm final state, landing and disarming

6.2.2 Ground Control Mode: Entry Conditions and Failsafes

Mission Checks Cover Known Rules; Environmental Judgment Is Still Needed

Vehicle state: positioning, altitude estimates, battery, attitude, and arming conditions meet mission needs.

Mission rules: pass geofence and required takeoff/landing-item checks; manually review waypoint distance warnings.

Abnormal conditions: configure executable responses to remote-control loss, data-link loss, battery issues, and invalid positioning.

Environment: separately check obstacles, terrain, takeoff/landing space, minimum turning radius, and payload.

Geofences limit permitted areas; failsafes specify abnormal-condition responses.

6.2.2 Ground Control Mode: Mission Start and End

Confirm the Mode at Start and the Final State at End

Stage	Requested Intent	Confirm From Feedback
Start	Ground station / RC switch / program requests Mission mode	Actual mode and armed state; mission items advancing
Normal end	Predefine Return, Land, or Hold to wait	Final position and task state; confirm touchdown for Land.
Unexpected interruption	Hold, Return, Land, etc., per condition and configuration.	Trigger cause and actual mode; check the action's prerequisites.

After landing, confirm disarming before recovery; Kill is for emergencies only.

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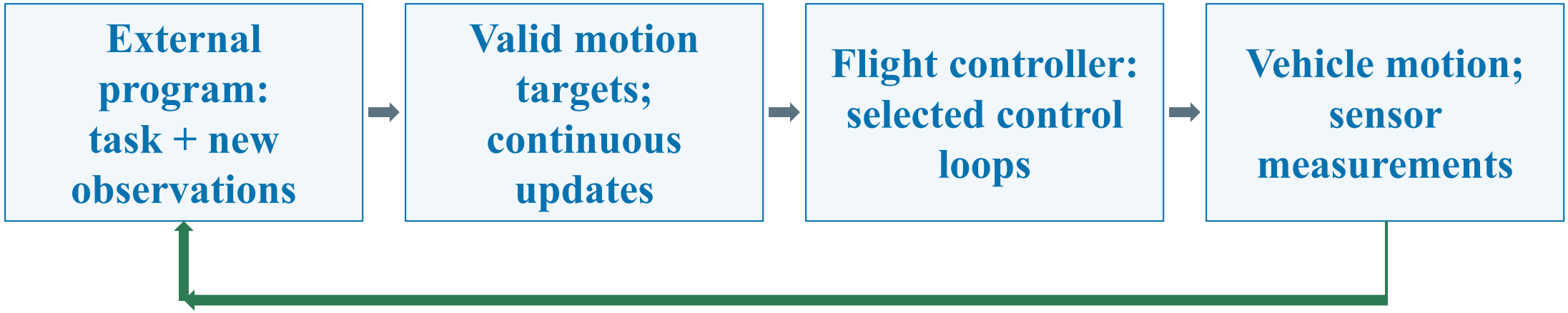
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Textbook: Secs. 6.1.2.3, 6.2.2.4 (entry and exit)

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6.2.3 Offboard Control Mode: Mechanism

External Programs Update Targets; the Flight Controller Runs the Selected Loops



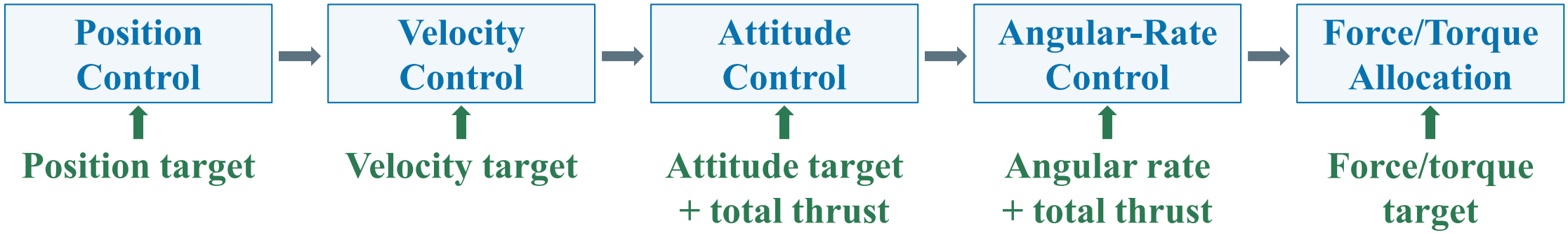
Current state feedback informs the external program's next decision.

Offboard control: a program outside the flight controller, on a ground or onboard computer, continually sends position, velocity, attitude or other targets over MAVLink.

Names: PX4 uses Offboard; ArduPilot's counterpart is Guided. Uses include visual tracking, multi-vehicle coordination, dynamic navigation and precision delivery.

6.2.3 Offboard Control Mode: Position, Velocity, Attitude, and Force

Choosing a Target Type Also Chooses Your Control Responsibilities



Green arrows mark external entry: the indicated loop and those to its right run in the flight controller; loops to the left run externally.

PX4 version, interface and vehicle determine supported combinations. Fields: 6.7, "Position Setpoints and Transmission."

Position/velocity: flight controller runs later loops and allocation; needs valid position/velocity estimates.

Attitude/angular-rate targets: supply total thrust externally; the flight controller retains unbypassed inner loops.

Force/torque: meet dynamics and actuator limits externally; flight controller performs supported allocation only.

6.2.3 Offboard Control Mode: Vehicle Types

The Same External Control Approach Needs Different Motion Constraints

Vehicle	Motion and Inputs	Constraints to Retain
Fixed-wing	Forward flight, turns, climb; waypoints/attitude and thrust	Airspeed, angle of attack, turning radius; no multicopter-style hovering
Multicopter / helicopter	Hovering and 3D motion; rotors/control mechanisms differ.	Translation couples to attitude; total thrust and tilt are limited.
Ground / surface	Speed, steering or heading; commonly underactuated.	Turning radius, road/currents; no arbitrary lateral motion.
Underwater vehicles, etc.	Propulsion, control surfaces, buoyancy, and payload actuators such as arms	Coordinate multiple actuators; use actual platform support.

6.2.3 Offboard Control Mode: External Control Workflow

Establish a Valid Target Stream Before Requesting the Mode

Connect and read states → **Confirm valid estimates** → **Pre-stream safe targets** → **Request mode / arm**

Pre-stream: targets also prove the program is still sending. Stream at >2 Hz before requesting the mode; v1.16 docs also require more than 1 s.

State confirmation: read actual mode and armed state; stop advancing on rejection or timeout.

Ongoing operation: repeatedly send targets, read states, and check for abnormal conditions.

Mode entry is one state transition; continuous control is an ongoing agreement.

6.2.3 Offboard Control Mode: Proof-of-Life Conditions

Proof of Life Shows the External Controller Is Still Running

$$f_{\text{live}} > 2\,\text{Hz}$$

Proof-of-life rate (Hz, messages/s)

Keep streaming before entry and during operation.
v1.16: start more than 1 s before entry.

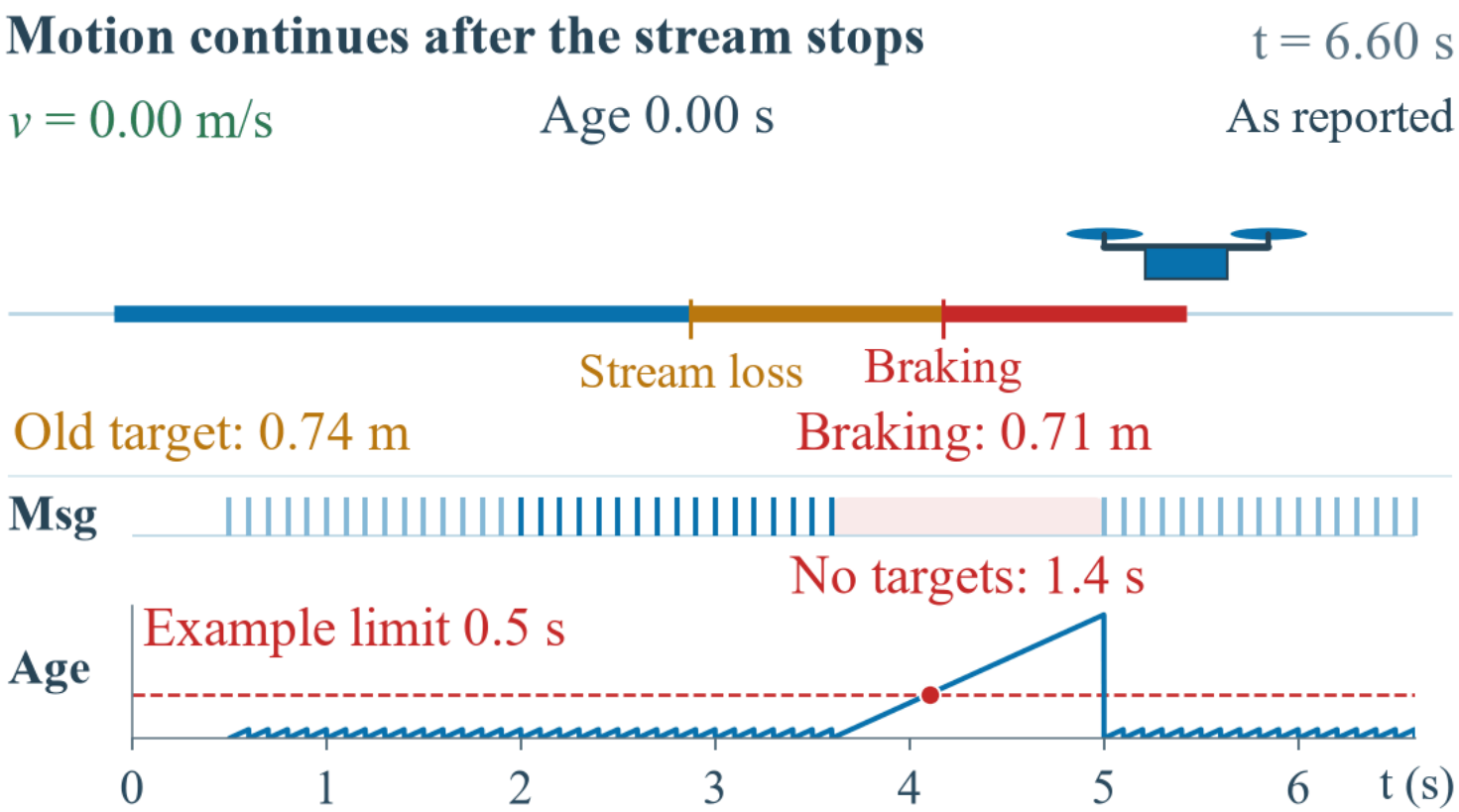
Interface	What Must Keep Streaming?	When Holding One Point
MAVLink Vehicle message protocol	Supported target messages also provide proof of life	Same position target; keep sending continuously
ROS 2 Robot Operating System 2	OffboardControlMode; targets via corresponding topics	Keep control-mode messages streaming; publish target topics as needed

PX4 v1.16 docs: entry, continued reception, and exit (v1.12 docs specify no 1 s requirement)

https://docs.px4.io/v1.16/en/flight_modes/offboard

6.2.3 Offboard Control Mode: Entry, Continuation, and Link Loss

Check Receipt Age and Actual Mode From Entry Through Recovery



Entry: check estimates; stream >1 s; request Offboard; read actual mode.

Receipt age: time since last target receipt. After stop, the old target runs until the age limit.

Reconfirm: read actual mode first; new messages do not imply resumed control.

Offboard entry, operation and loss response (teaching example, not platform measurements).

6.2.3 Offboard Control Mode: Reproducible Reception Timing

An Adequate Average Rate Can Still Contain a Timeout Gap

Teaching calculation: 0–3 s at 0.1 s gives 31 messages; missing 8 leaves 23 received.



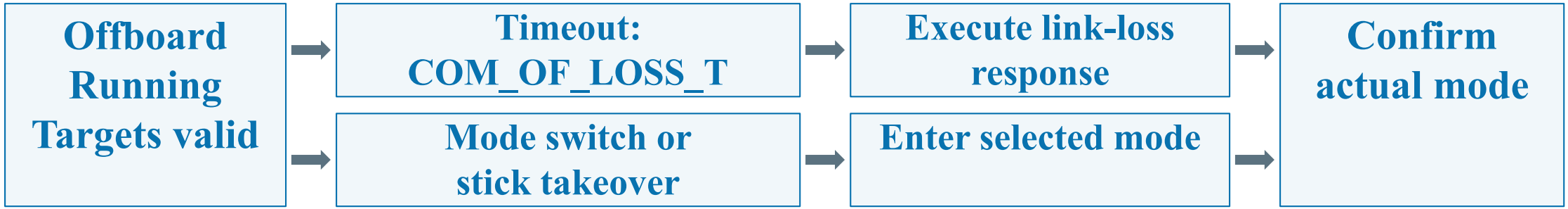
$$f_{\text{avg}} = \frac{23 - 1}{3 - 0} = 7.33\ \text{Hz}$$

0.5 s (example): timeout
1.0 s (default): no trigger

23 messages: 22 intervals over the first-to-last 3 s; threshold COM_OF_LOSS_T.
A valid average can still time out; check receipt age throughout (see 6.7).

6.2.3 Offboard Control Mode: Timeout and Takeover

Link-Loss Response and Manual Takeover Have Different Triggers



Timeout: COM_OF_LOSS_T (s; default 1.0). Loss occurs when latest-target age exceeds it.

Exit response: v1.12.3 with RC uses COM_OBL_RC_ACT (default Position); without RC, COM_OBL_ACT (default Land).
v1.14 and later use only COM_OBL_RC_ACT.

Manual takeover: use the mode switch; COM_RC_OVERRIDE controls stick takeover, enabled by default only in automatic modes, not Offboard.

Loss: automatic per parameters. Manual takeover: mode switch or enabled stick override.

6.2.3 Offboard Control Mode: Normal Exit

Hand Over Control, Confirm Disarming, Then Clean Up Communication



State evidence: jointly confirm final task state, actual mode, landed state, and armed state.

Order: confirm landing or takeover mode, then stop target streaming. Call stopRun() only after confirmed touchdown and disarming.

endOffboard(): sends no landing command. See 6.7, “SDK Side Effects” (SDK: software development kit),
and “Termination and Exceptions” for behavior and shutdown order.

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Textbook: Secs. 6.1.2.1–6.1.2.3

6.2.4 Comparison on a Common Task: Inspection

The Same Inspection Task Places Ongoing Decisions in Different Hands

Dimension	Remote Control	Mission Mode	Offboard Control
Input	Stick inputs and mode	Waypoints and task actions	Continuous motion targets
Continuous updater	Operator	Onboard mission executor	External program
Feedback use	Operator decides next; flight controller stabilizes motion	Onboard arrival checks; ground station monitors.	External target updates; flight controller executes.
Suitable scenarios	On-site judgment Manual intervention	Known routes Repeated inspections	Dynamic tracking Real-time adjustment

6.2.4 Comparison on a Common Task: Task Changes

Who Changes the Route When a New Obstacle Appears?

Method	Who Handles the New Obstacle?	Prerequisites
Remote control	Operator judges and adjusts inputs; enter Hold or exit if needed.	Timely observation and communication; keep an executable takeover mode.
Mission mode	Supported avoidance module; or pause, replan, and update mission	Confirm progress and where to resume; waypoints do not imply obstacle avoidance.
Offboard control	External perception and planning continually provide new valid targets.	Valid perception, planning and state estimates; meet interface liveness and motion constraints.

Modes provide control entry; perception and planning determine responses to new changes.

6.2.4 Comparison on a Common Task: Abnormal Conditions and Takeover

After a Link Breaks, Identify What Was Lost

Lost input/link	Direct Effect	Evidence to Read
Remote-control input	The operator can no longer update stick inputs	Remote-control validity, loss cause, actual mode and takeover conditions.
Ground data link	Ground monitoring/changes are lost; the onboard mission may remain.	Mission item, data-link-loss action, actual mode and mission configuration.
Offboard target stream	External targets lose validity; Offboard loss may be triggered.	Message timing, actual mode, estimate validity, timeout and exit-action configuration.

Takeover is confirmed by actual mode and control response, not by sending a request.

Classroom Exercise

Identify Control Authority and the Next Evidence to Check

Situation	Assessment	What to Observe or Do
Multicopter in Altitude mode drifts horizontally after stick release.	Altitude is held; horizontal position is not guaranteed.	Check mode and altitude response; position hold needs positioning and Position mode.
Upload accepted, but mission not started.	Only onboard mission acceptance is confirmed.	Check start request, actual mode, execution prerequisites and current item.
Messages: 0, 0.2, 0.4, 1.6, 1.8, 2.0 s; default threshold 1.0 s	Mean: 5÷2 s=2.5 Hz>2 Hz; 1.2 s gap → loss at 1.4 s.	Switch modes per loss response; when messages resume at 1.6 s, read actual mode first.

Classroom Exercise

New Obstacle: First Identify Who Can Change the Route

Situation	Assessment	What to Observe or Do
Mission-mode inspection: a new crane blocks the route; obstacle avoidance is off.	Executor follows original waypoints; no automatic detour.	Pause or enter Hold; edit and upload waypoints; confirm current item before restarting.
Offboard program interpolates preset waypoints as position targets; no perception module.	Offboard only supplies the target interface; the program still sends the original route.	Add perception/planning to revise targets; otherwise, an operator takes over.
Remote control: toward an obstacle at 5 m/s; video delay 1 s.	Operator reroutes; before viewing, extra travel: 5 m/s × 1 s=5 m	Slow down and increase clearance; enter Hold if needed.

Section Summary

Choose Modes by Input Meaning, Update Responsibility, and Final State

Remote control: check how the flight mode interprets sticks; manual operation can still have closed-loop assistance.

Mission mode: plan and upload, then start and monitor; explicitly specify the final task state.

Offboard control: design target types, valid estimates, proof of life, and exit actions together.

Common-task comparison: modes provide control entry points; perception and planning handle new obstacles.

Common errors: input channels are not motor outputs; stopping a program is not landing; an adequate average rate can still time out; SDK initialization disables loss failsafes; entering Offboard does not provide obstacle avoidance.