Lecture 7: Introduction to Aerospace Guidance and Control Systems

Textbook Sections 11.2, 11.3, & 11.5

Dr. Jordan D. Larson

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  - Allows robustness for many dynamics assumptions
- High maneuverability may require more complicated MIMO techniques
  - Robust optimal control for aerospace vehicles

Control of MIMO Systems

- Multiple input/multiple output (MIMO) systems, e.g., aerospace vehicles: state-space methods to develop suitable controllers
  - Adaptive control
  - Robust control
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  - Optimal control

- Systems with few number of inputs and/or outputs: different outputs may have responses on different time scales
  - Allow SISO methods to be applied at these different time scales through cascade control

Example System with Different Time Scales

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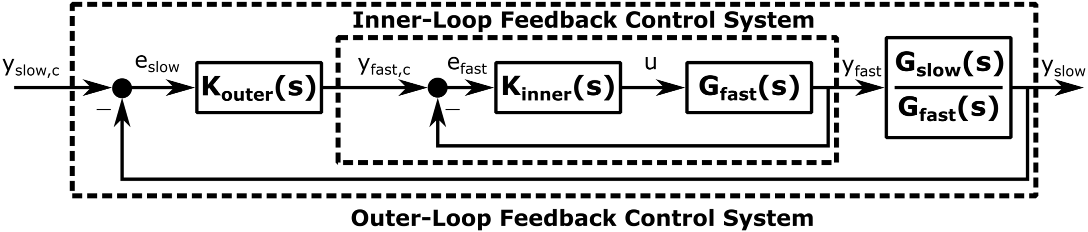
- Assume y_{fast}, y_{slow} related through ≥ 1 integration
  $\rightarrow$ denominator of $\frac{G_{slow}(s)}{G_{fast}(s)}$ at least order one higher in s than numerator

Cascade Control

- Consider two linked inner-outer feedback control systems:



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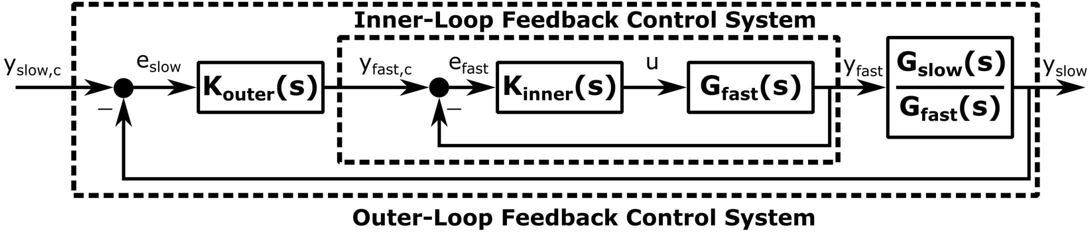

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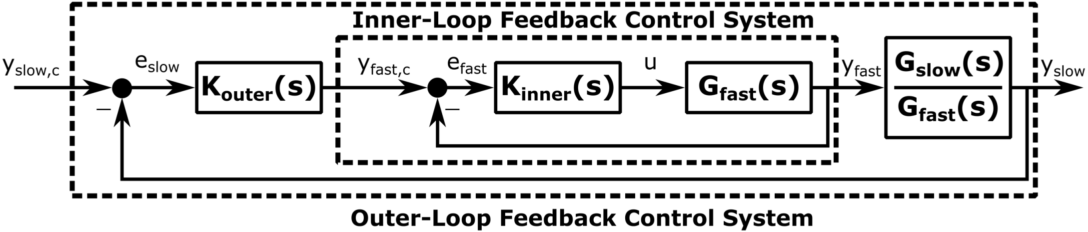

- Known as:
  - **Cascade control**
  - **Nested-loop control**
  - **Inner-outer loop control**
- With proper loop-shaping: simple design & *also* robust SISO LTI system

Cascade Control Design

- Design $K_{inner}(s) \rightarrow y_{fast}$ tracks $y_{fast,c}$ for $\omega \leq \omega_{c,inner}$
  - Inner-loop feedback control system transfer function from $y_{fast,c}$ to y_{fast}:

$$\frac{y_{fast}(s)}{y_{fast,c}(s)} \approx \frac{\omega_{c,inner}}{s + \omega_{c,inner}} \tag{5}$$

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- Two-step approach much simpler than one-step coupled approach

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- Systems with natural frequency separation between $G_{outer}(s)$ and $G_{inner}(s)$ make cascade-loop control physically realizable method
- Frequency separation must be conserved when performing loop-shaping of inner- and outer-loops
  - Standard loop-shaping of $L_{inner} = G_{inner}K_{inner}$ & $L_{outer} = G_{outer}K_{outer}$
    sets $|L_{inner}|$ large for $\omega < \omega_{c,inner}$, small for $\omega > \omega_{c,inner}$
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  - Bandwidths
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- Note: multiple inner-loops cascaded
  - Typical for vehicle feedback control systems

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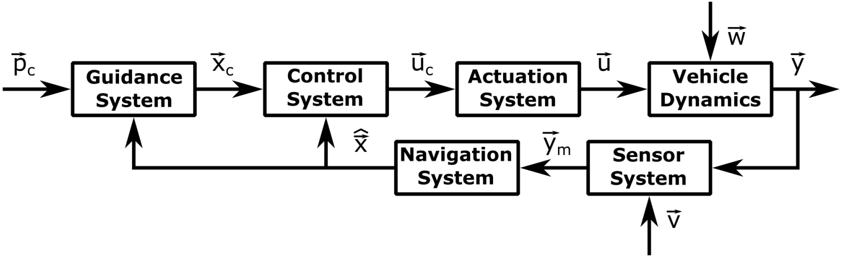

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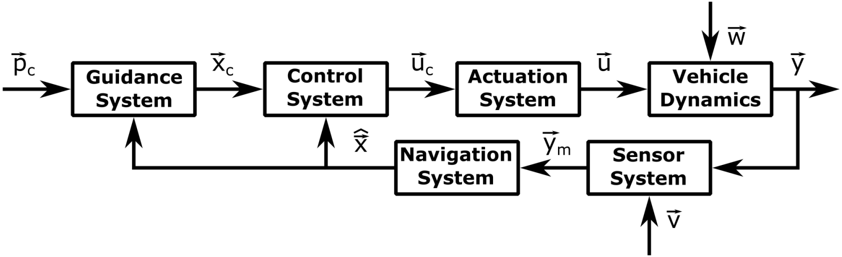

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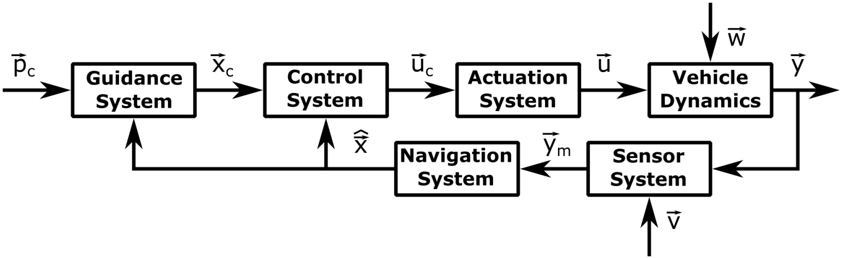

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- Manual control: guidance and control system as human operator, not computer

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- **Navigation**: **vehicle (self-) state estimation**

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- As control systems include direct manipulation of forces/moments applied to vehicle through some sort of physical phenomena $\rightarrow$ consider effects of any **actuation system** on GNC system
  - Coupled with vehicle dynamics, actuator dynamics play vital role in control system design for vehicles

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  - Sequence of **waypoints** connected by lines:
    - Switching of lines connecting waypoints: planning system
    - Assesses current position estimate of aerospace vehicle
    - Often uses some success and feasibility criteria checks on reaching each waypoint

Planning and Tracking Systems

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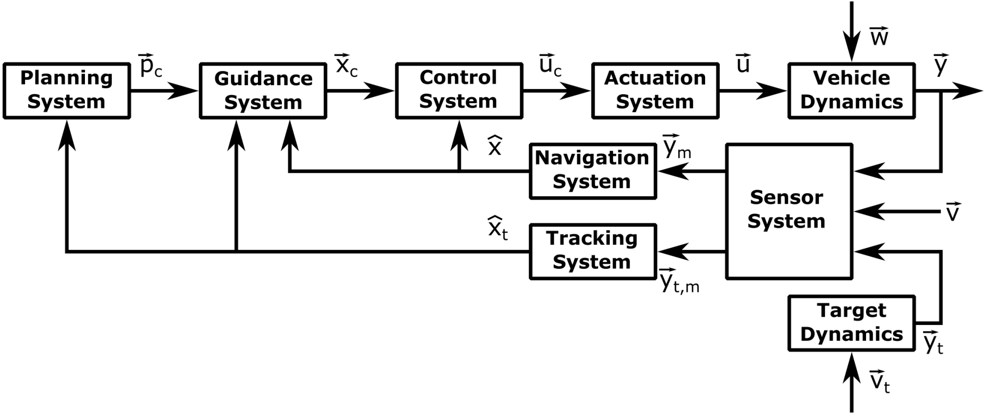
- If dynamic/uncertain target: **tracking system** necessary for planning/guidance
  - If > 1 target specified: planning system must have feedback from navigation & target tracking systems to assess target switching/assignment

General Planning, Tracking, and GNC System



- Also possible: multiple aerospace vehicles interconnected known as teams/swarms

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    - Gain scheduling of aircraft typically require estimation of current flight conditions in real-time: onboard sensor system known as **air data system (ADS)**
        - Provide measurements of aerospace vehicle’s surrounding air mass, i.e. **air data**: typically quantified as airspeed, angle of attack, sideslip angle, perhaps altitude & rate of climb
        - Airspeed, angle of attack, sideslip angle a.k.a. **air data triplet**

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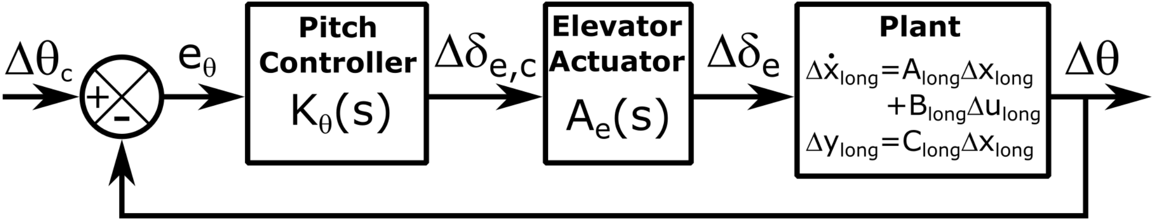
- Outer-loop: guidance for attitude commands and rate-of-climb

Pitch Controller

- Longitudinal inner-loop control system design for airplane typically uses:
  - Pitch control law, $K_\theta(s)$
  - Longitudinal LTI plant model



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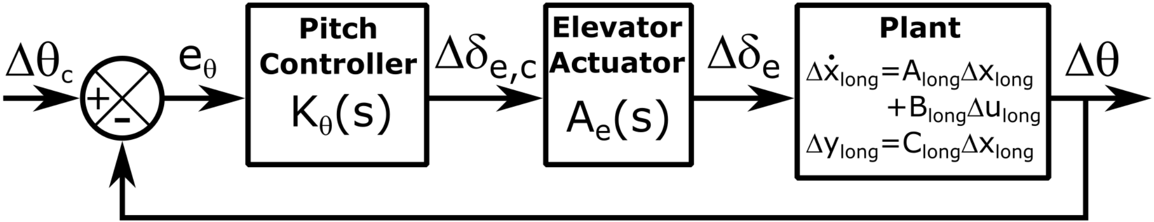

- Other alternatives for inner-loop include pitch rate Δq and angle of attack $\Delta\alpha$ as single output for system to track with inner-loop

Auto-Throttle Control Outer-Loop

- Pitch attitude control important analysis at steady-flight condition: whether an increase in $\Delta\theta_c$ leads to increase or decrease in flight-path angle $\Delta\gamma$ as $t \to \infty$
  - If on "front side of power curve," i.e. a reduction in v_∞ requires less power to maintain level flight: $\Delta\theta_c > 0 \to \Delta\gamma > 0$ as $t \to \infty$
  - If on "back side of power curve," i.e. a reduction in v_∞ requires more power to maintain level flight: $\Delta\theta_c > 0 \to \Delta\gamma < 0$ as $t \to \infty$

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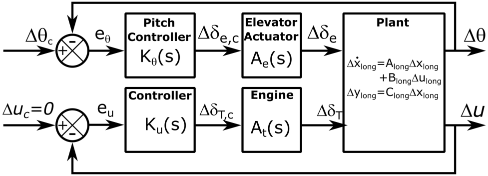
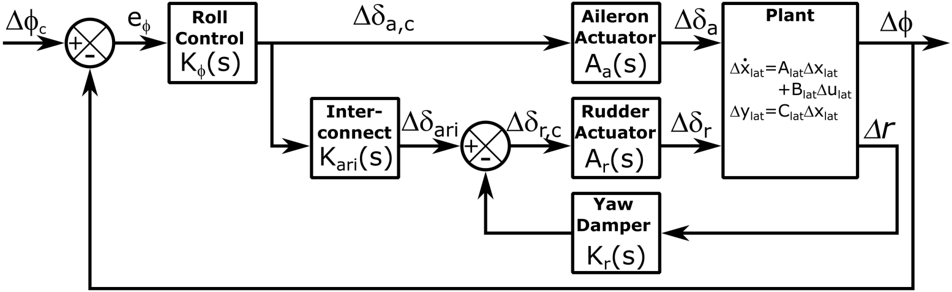
- To overcome coupling between $\Delta\theta_c$, $\Delta\gamma$, and v_∞: δ_T in **auto-throttle** outer-loop to command Δu_c to account for change in v_∞ due to command in $\Delta\theta_c$:



Roll Controller

- Lateral-directional inner-loop control system for airplane typically uses:
  - Roll control law, $K_{\phi}(s)$,
  - Yaw damper, $K_r(s)$
  - ARI $K_{ARI}(s)$
  - Lateral-directional LTI plant model



Roll Controller for Coordinated Turns

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- Washout filter stage included in yaw damper for sustained turns where yaw rate non-zero
  - Without it, yaw damper would tend to “fight” turn by maintaining rudder deflection opposite to desired for turn

Roll Controller for Coordinated Turns

- Coordinated turn, i.e. $\beta = 0°$ with $\Delta\phi_c \neq 0°$, with ARI
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- ARI: one method
  - Alternatives: feedback to rudder of β, a_y, r

Turn Compensation

- When performing coordinated turn, also generate suitable longitudinal control inputs to maintain altitude: **turn compensation**
  - By rotating lift vector of airplane, vertical component of lift must still counteract weight for constant altitude
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- Use computed yaw rate and roll angle to generate commanded pitch rate for $\Delta\theta$ or Δq feedback control system:

$$q_c = r \tan \phi \tag{6}$$

  - Values for entire airplane, not perturbed states

Longitudinal Speed Hold

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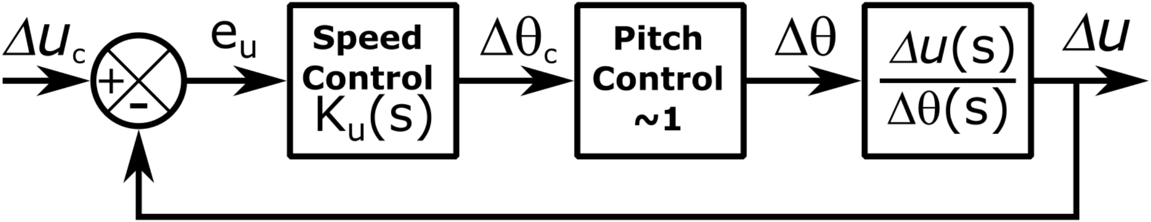

Longitudinal Speed Hold (continued)

- Inner-loop of speed hold control loop uses elevator: form outer-loop plant

$$\frac{\Delta u(s)}{\Delta\theta(s)} = \frac{\text{num}\left(\frac{\Delta u(s)}{\Delta\delta_e(s)}\right)}{\text{num}\left(\frac{\Delta\theta(s)}{\Delta\delta_e(s)}\right)} \tag{7}$$

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- Note: $K_u(s)$ or $\frac{\Delta u(s)}{\Delta\theta(s)}$ may need to be negative as positive change in pitch $\Delta\theta$ may cause reduction in flight velocity u

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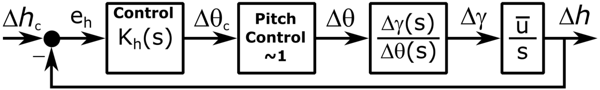

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- Note: required that increase in pitch angle θ must produce steady-state flight path

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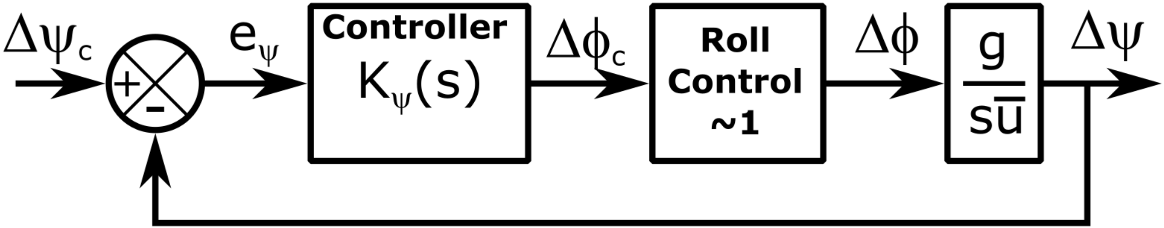

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- Note: often roll angle must be hard limited for particular airplane missions.
  - **Limiter** for roll: limits maximum and minimum values to specified values
  - Inclusion introduces nonlinearity: generally reduces speed of response for fast maneuvers
  - Performance typically assessed through nonlinear simulations initially designed with linear models

Precision Approach Motivation

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- Systems designed to supply information using radio signals interpreted by specialized equipment onboard airplane which supply heading correction that pilot or autopilot must make to continue on planned descent trajectory to airport runway
  - Systems maintained by individual airports
  - Reference trajectories for guidance systems constant, predefined trajectories based on the topography of area, layout of airport runways, and regulations concerning safety for airplane descent

Precision Approach Categories

- Important parameter in precision approaches: **decision height (DH)** or **decision altitude (DA)**
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- DH/DA denotes height/altitude in which missed approach procedure must be started, does not preclude airplane from descending below prescribed DH/DA

Precision Approach Categories

- For precision approach guidance: four categories which allow decision heights to be lowered

Category	DH	RVR
I	$>$ 60 m	$>$ 550 m
II	30-60 m	$>$ 350 m
III A	$<$ 60 m	$>$ 200 m
III B	$<$ 15 m	$>$ 50 m
III C	none	none

- To allow these precision approaches, two primary technologies serve commercial airplanes as both navigational and guidance aids

Instrument Landing System

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  - Indicate correction that the pilot or autopilot must make
  - Displayed to pilots as point plotted on 2 coordinate axes whose origin denotes no error, i.e., if airplane left of reference trajectory, point right of origin, if airplane above reference trajectory, then point below origin
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- **Marker beacons**: provide distance to runway information at setpoints along approach
- **Distance measuring equipment (DME)**: provide continuous distance to runway

Ground-Based Augmentation System

- Due to rapid development of Global Navigation Satellite Systems (GNSS), in particular, Global Positioning System (GPS) run by U.S. DoD, most recent advances in automatic guidance technologies for airplanes include following technologies which enhance basic capabilities of GNSS by reducing errors found in GNSS signals thereby improving accuracy of navigation solution

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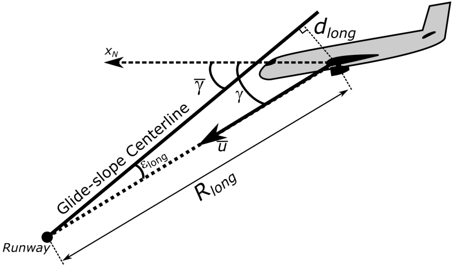
- GBAS anticipated to replace ILS in future

Glide-Slope Guidance



- Precision approach guidance, airplane follows "straight-line" path in longitudinal plane for glide-slope
- d_{long}: longitudinal position deviation
- ϵ_{long}: longitudinal angular deviation
- R_{long}: longitudinal range to intercept
- $\bar{\gamma}$: reference glide-slope angle

Glide-Slope Guidance (continued)

- Longitudinal deviations:

$$\sin \epsilon_{long} = \frac{d_{long}}{R_{long}} \tag{13}$$

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$$\epsilon_{long} = \bar{\gamma} - \gamma = -\Delta\gamma \tag{15}$$

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$$\dot{\epsilon}_{long} \approx \frac{\bar{u}}{R_{lat}}\Delta\gamma \tag{19}$$

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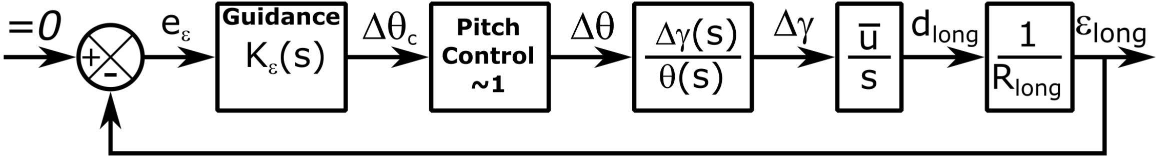
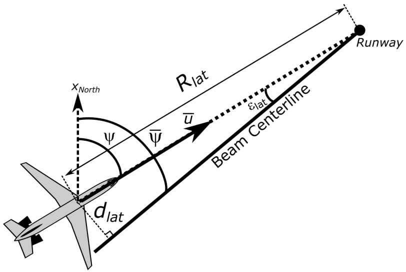
- Assumes body-fixed reference frame as stability frame, i.e., $\bar{\alpha} = 0$, thus $\bar{\gamma} = \bar{\theta}$

Glide-Slope Guidance (continued)



- Form block diagram of **glide-slope guidance system**:
- Very similar to altitude hold feedback loop with additional outer-loop guidance for reducing angular deviation from reference flight-path to zero which scales inversely with distance R_{long} from runway

Localizer Guidance



- Precision approach guidance, airplane follows "straight-line" path in lateral-directional plane for localizer
- d_{lat}: lateral-directional position deviation
- ϵ_{lat}: lateral-directional angular deviation
- R_{lat}: lateral-directional range to intercept
- $\bar{\psi}$: reference beam centerline for localizer

Localizer Guidance (continued)

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- Lateral angular deviation related to heading angle:

$$\epsilon_{lat} = \psi - \bar{\psi} \tag{23}$$

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- Transfer function:

$$\frac{\epsilon_{lat}(s)}{\Psi(s) - \bar{\Psi}(s)} \approx \frac{\bar{u}}{Rs} \tag{28}$$

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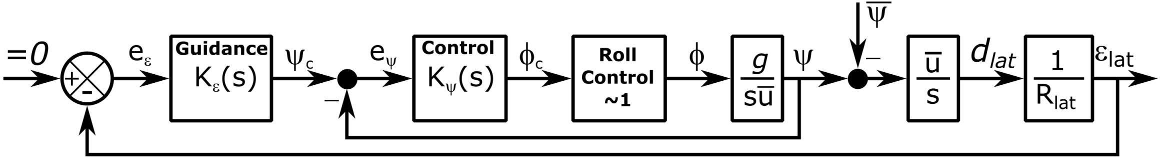
$$\dot{\epsilon}_{lat} \approx \frac{\bar{u}}{R_{lat}}\left(\psi - \bar{\psi}\right) \tag{27}$$

- Transfer function:

$$\frac{\epsilon_{lat}(s)}{\Psi(s) - \bar{\Psi}(s)} \approx \frac{\bar{u}}{Rs} \tag{28}$$

- Assumes body-fixed reference frame as stability frame, i.e., $\vec{v} = u$ and coordinated flight occurring, i.e., $\bar{\beta} = 0°$

Localizer Guidance (continued)



- Block diagram of **localizer guidance system**
- Uses heading hold feedback loop with additional outer-loop guidance for reducing angular deviation from reference heading to zero which scales inversely with distance R_{lat} from runway

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  - (Attitude) Control Systems
  - Actuation Systems
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- Guidance loops often use simplified point-mass plant models in design phase
  - Simulate full system in system verification and validation (V&V)