16.400/453J

Human Factors Engineering

Manual Control II

Massachusetts Institute of Technology

Pilot Input

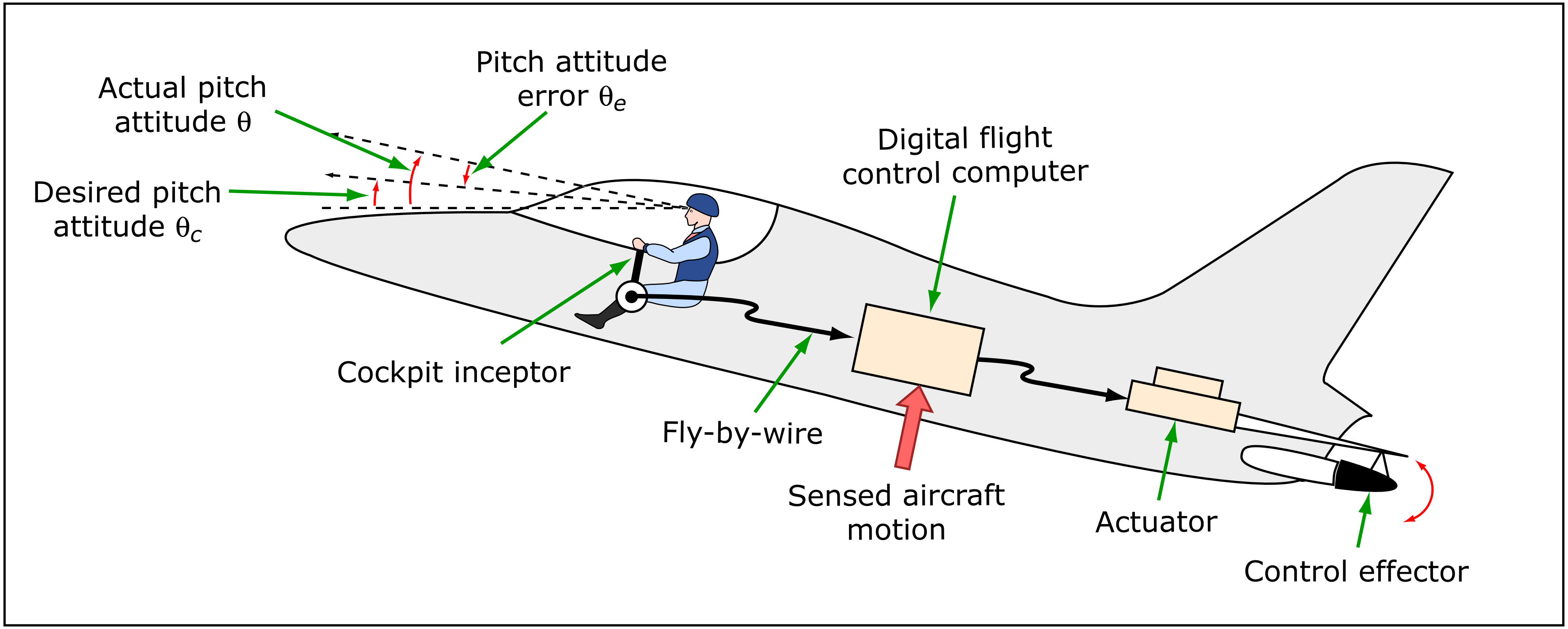
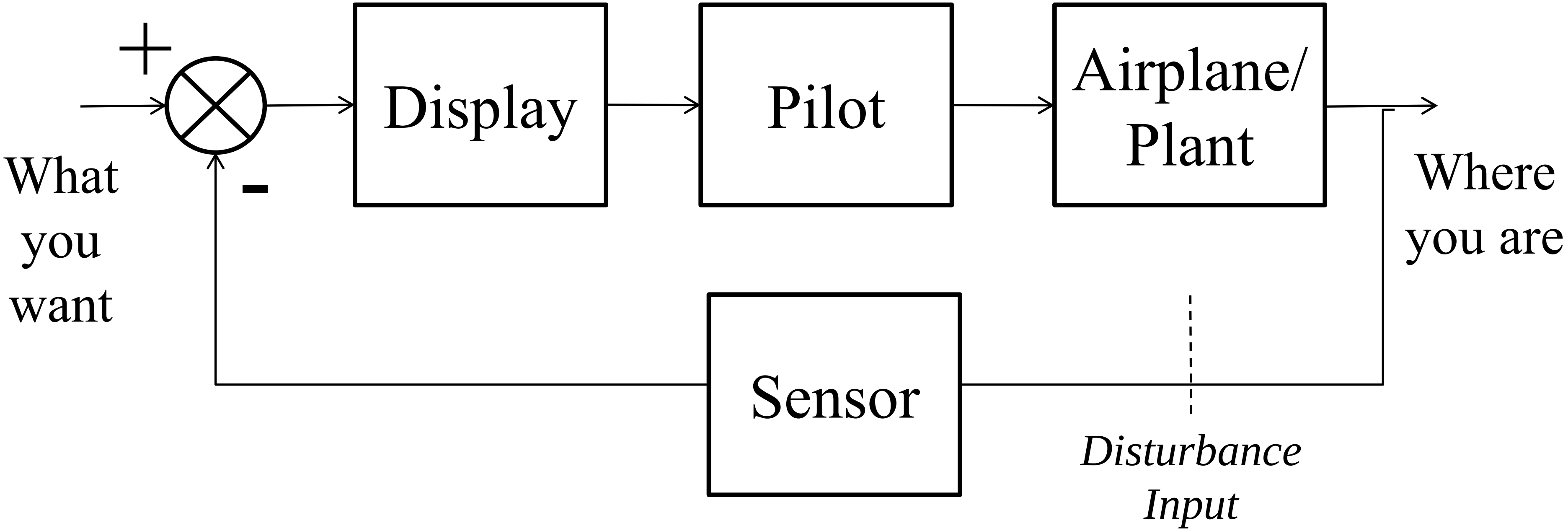


Image by MIT OpenCourseWare.

The Basic Pilot/Plant Feedback Loop

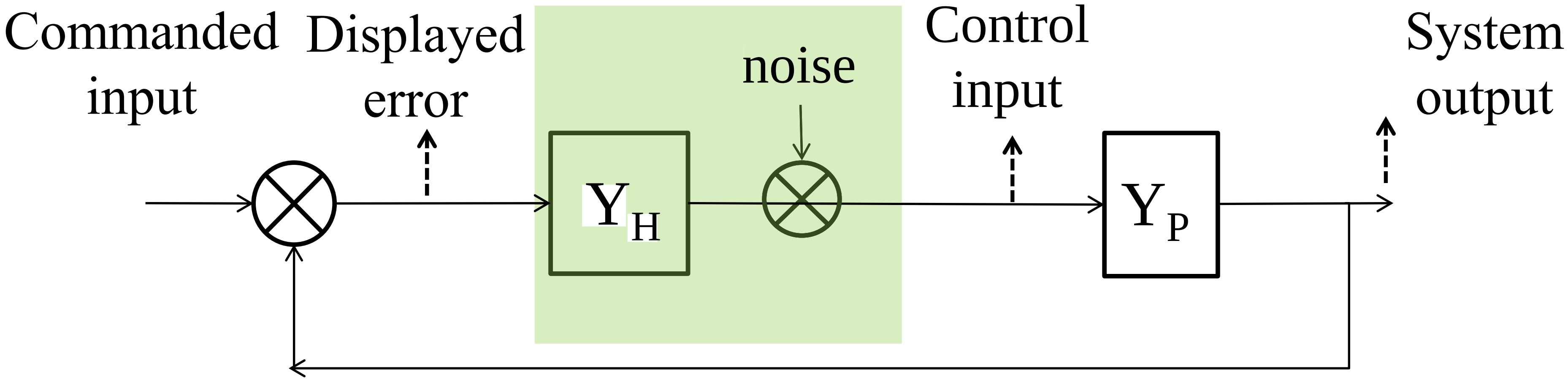


- Modeling the system
  - Human modeling is notoriously problematic
    - Save for manual control, tracking tasks
  - Implications for supervisory control systems

Modeling & Design

- Models help us design the "system" to promote the best performance
  - System = human + computer
  - Performance depends...
    - Stability
      - Bounded output for bounded input
    - Maneuverability
    - Pilot skill
- Two human models
  - Crossover
  - Optimal control

Modeling the Human Pilot



- One dimensional compensatory tracking example
- Significant assumption of linearity
    - A “correct” assumption with noise input because humans perform most linearly with random inputs
    - Or valid under stationary tracking with highly trained operators
- Operator/pilot describing function
    - Not a true transfer function due to linear approximation

System response to a control input

- Attitude command

$$\theta(t) = K\delta(t) \quad \theta(s) = Kd(s) \quad \frac{\theta(s)}{\delta(s)} = K$$

- Attitude-rate command

$$\dot{\theta}(t) = K\delta(t) \quad s\theta(s) = K\delta(s) \quad \frac{\theta(s)}{\delta(s)} = \frac{K}{s}$$

- Attitude-acceleration command

$$\ddot{\theta}(t) = K\delta(t) \quad s^2\theta(s) = K\delta(s) \quad \frac{\theta(s)}{\delta(s)} = \frac{K}{s^2}$$

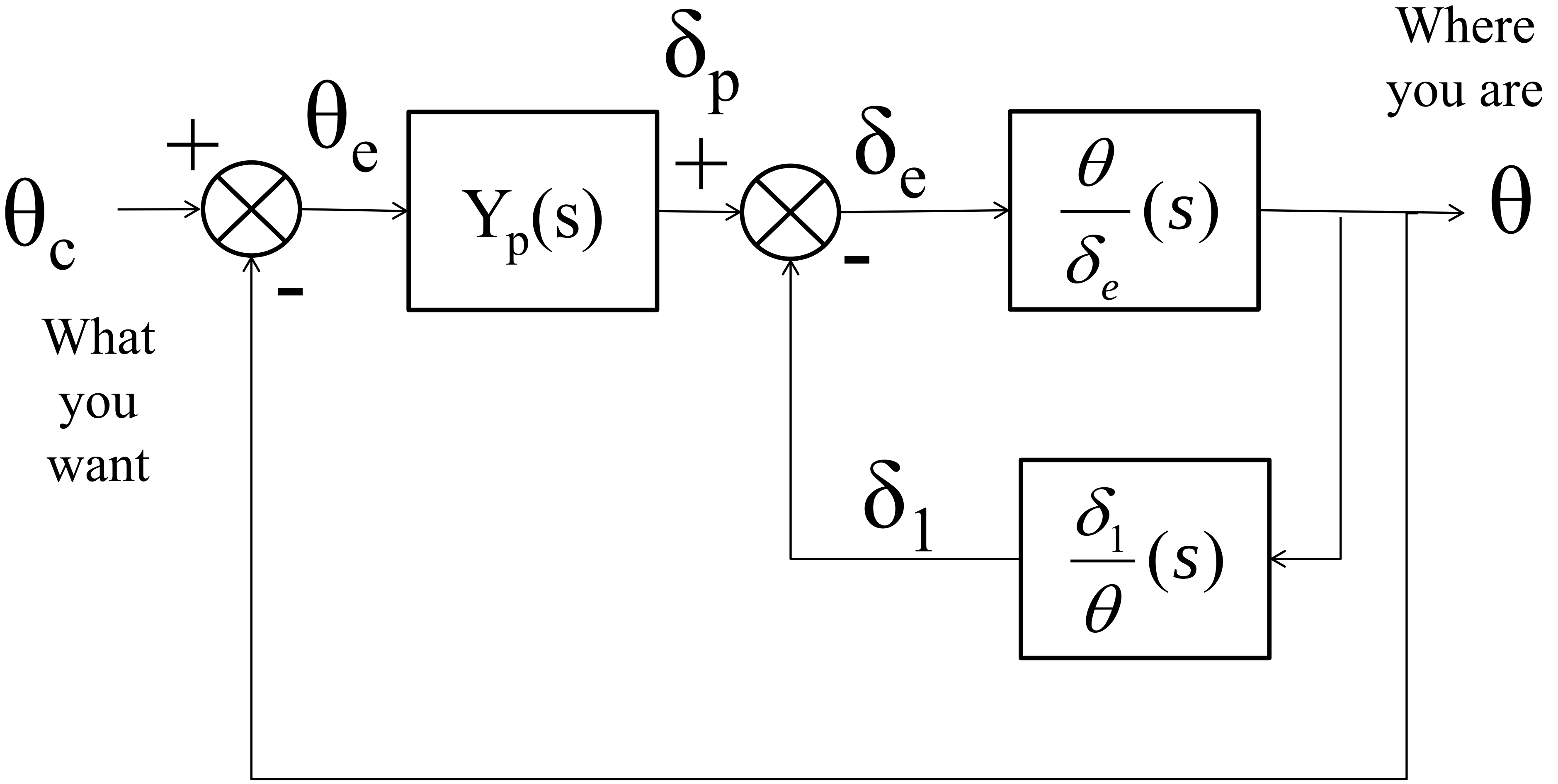
- Time delays

$$e^{-\tau s}\theta(s)$$

- Lag $\frac{k}{s+k}$

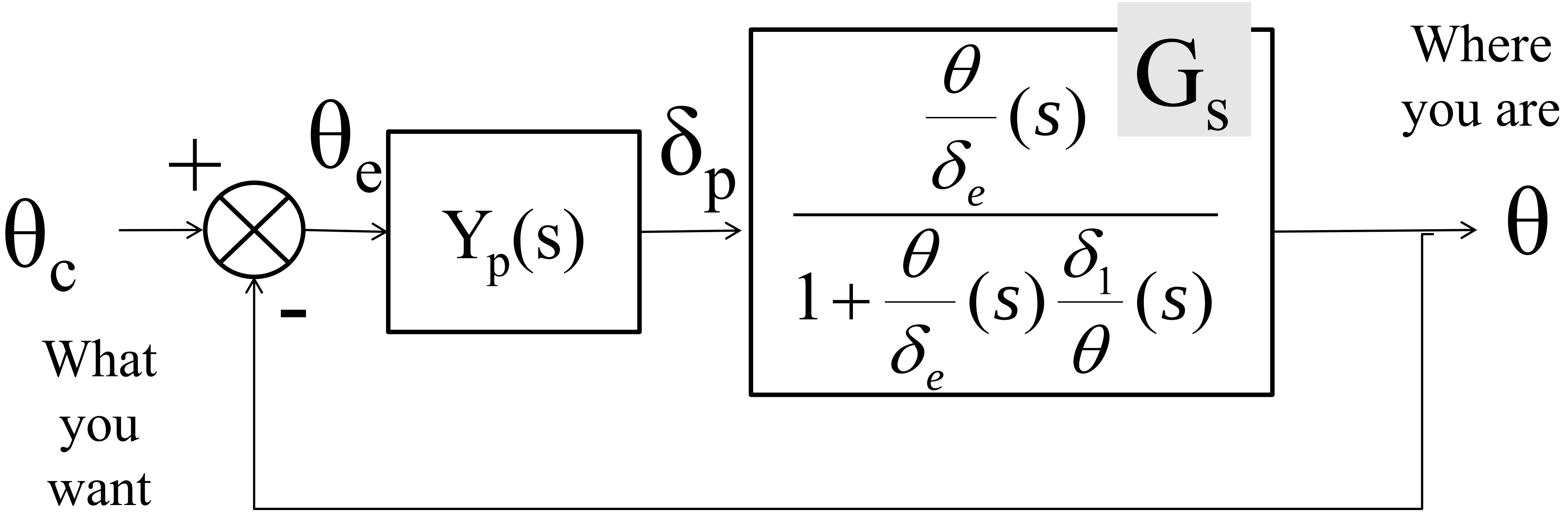
k = 1 (unity gain)

Pilot/Plant Feedback Loop I



Negative feedback system (reduces error)

Pilot/Plant Feedback Loop II



$$\frac{\frac{\theta}{\delta_e}(s)}{1+\frac{\theta}{\delta_e}(s)\frac{\delta_1}{\theta}(s)}$$

$$\frac{\theta}{\theta_c}(s)=\frac{Y_p(s)G(s)}{\underbrace{1+Y_p(s)G(s)}}$$

Open loop transfer function

Closed loop transfer function

Optimal Performance & the Bode Plot

- Bode plot helps us see output/input ratios for signal amplitude and phase shift
- 1st order system

$$\frac{\theta(s)}{\delta(s)} = \frac{Ke^{-\tau s}}{s}$$

  - -20db drop for each frequency decade increase
  - Pure integrator causes 90° phase shift
  - Time delay dominates at high freqs

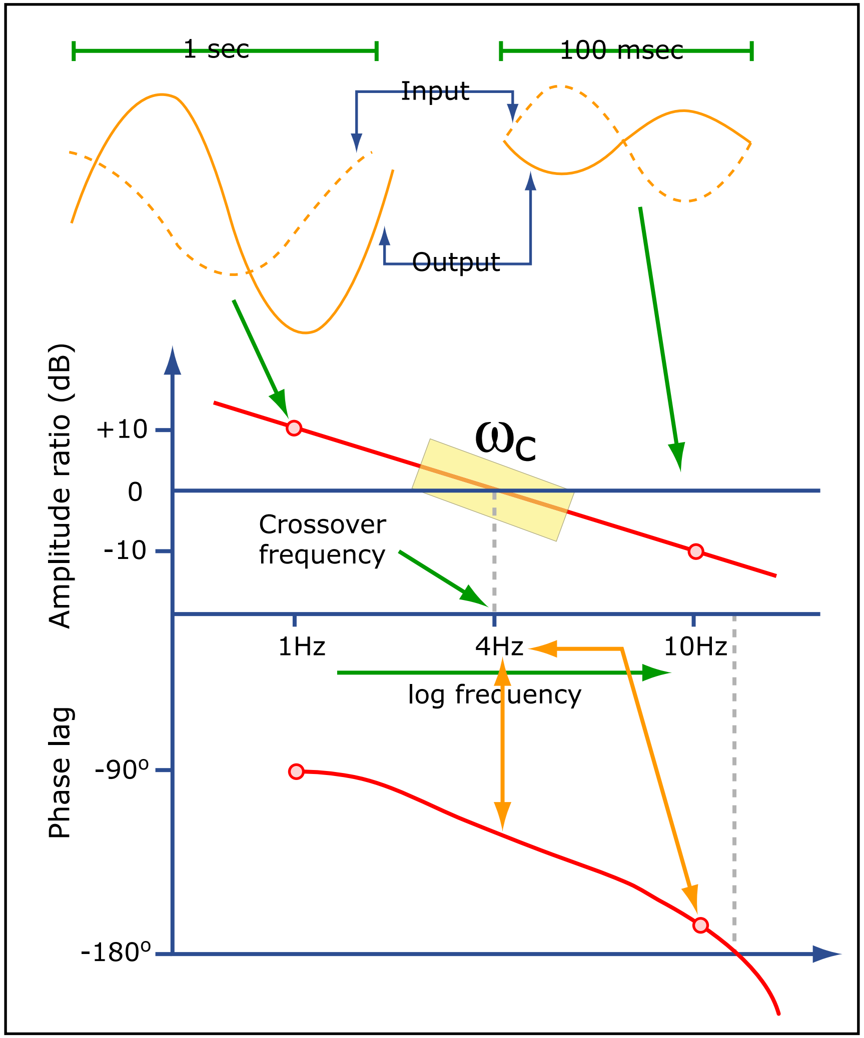


Image by MIT OpenCourseWare.

Systems Order & the Bode Plot

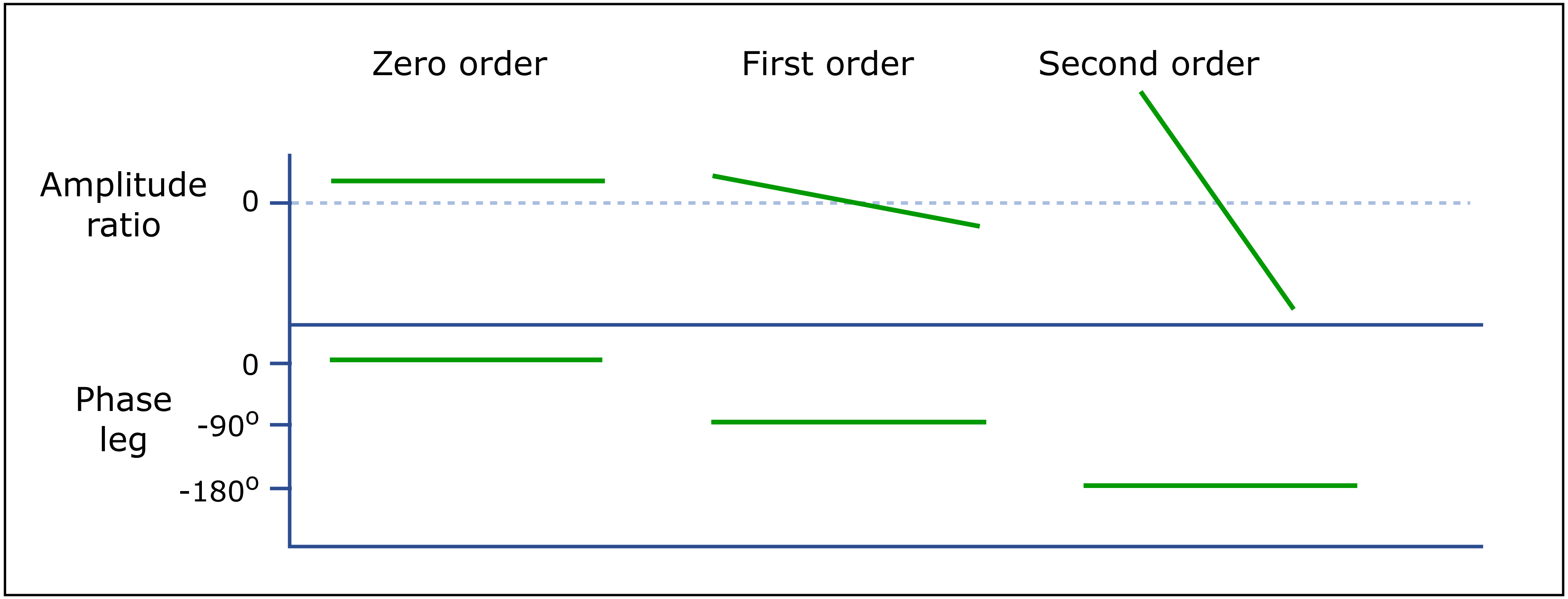


Image by MIT OpenCourseWare.

- Each order adds a 90° phase lag & -20db/decade
- Time delay exacerbates errors
- Integrator: rate of change of control movement is proportional to error

Bode Plot Elements

Open Loop TF

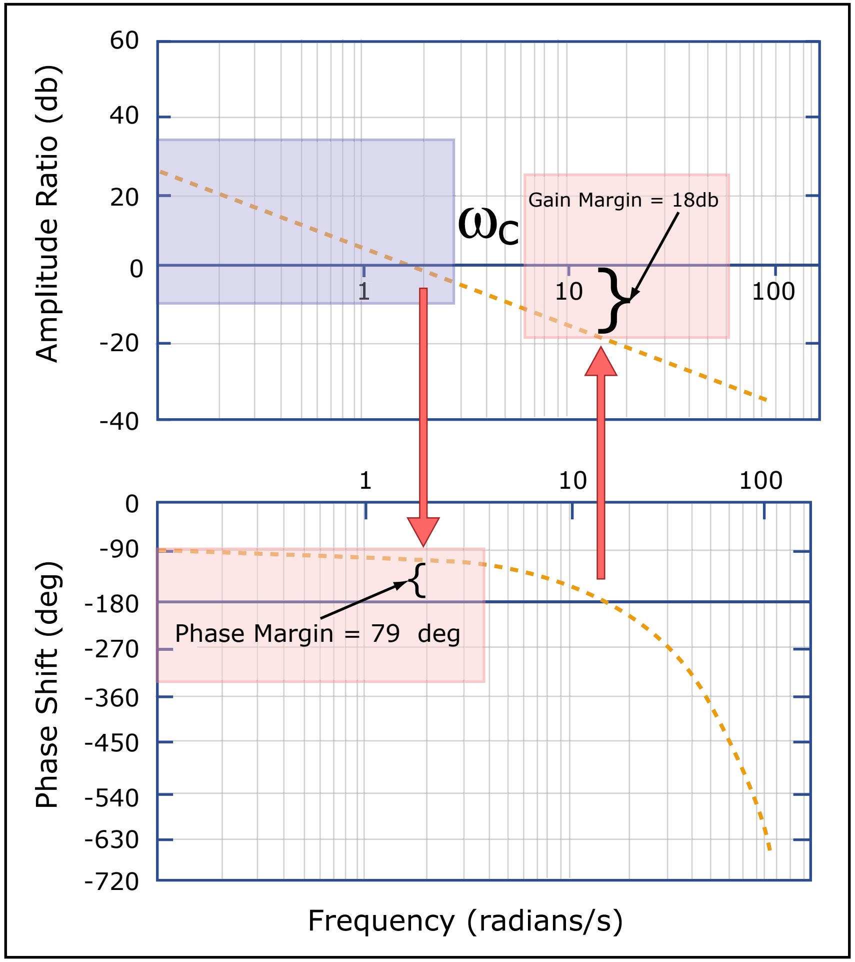


Image by MIT OpenCourseWare.

Closed Loop TF

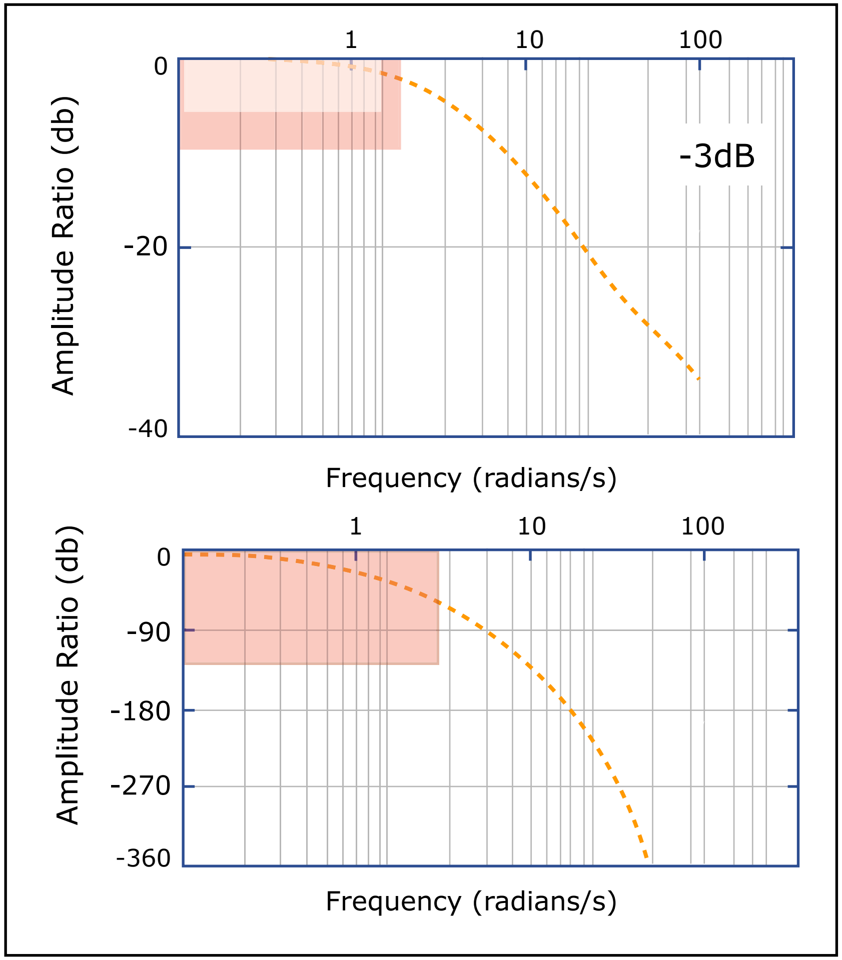


Image by MIT OpenCourseWare.

Crossover Frequency Concerns

- The range of frequencies over which the systems responds satisfactorily
  - We want to maximize, why?
- Open loop crossover frequency determines the bandwidth of the response of closed loop system
- For stability, OL gain must go through 0 dB before phase shift = -180
  - Nyquist stability criterion
- Human pilot dynamics ultimately place upper limit on attainable OLTF ωc
  - Time delay adds phase lag
  - .1-.25 s is typical

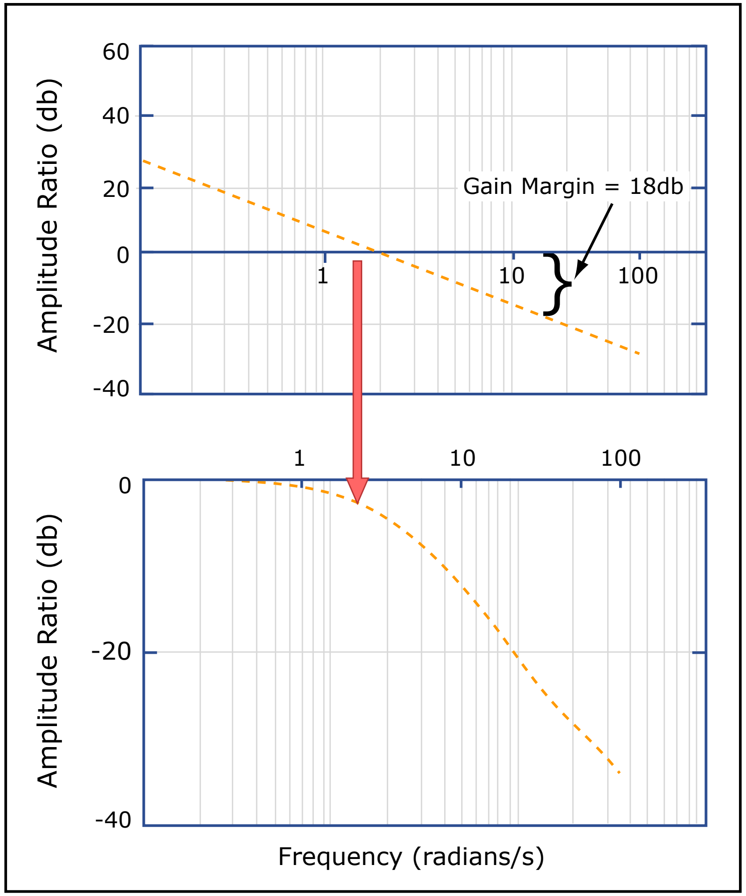


Image by MIT OpenCourseWare.

Stable vs. Unstable

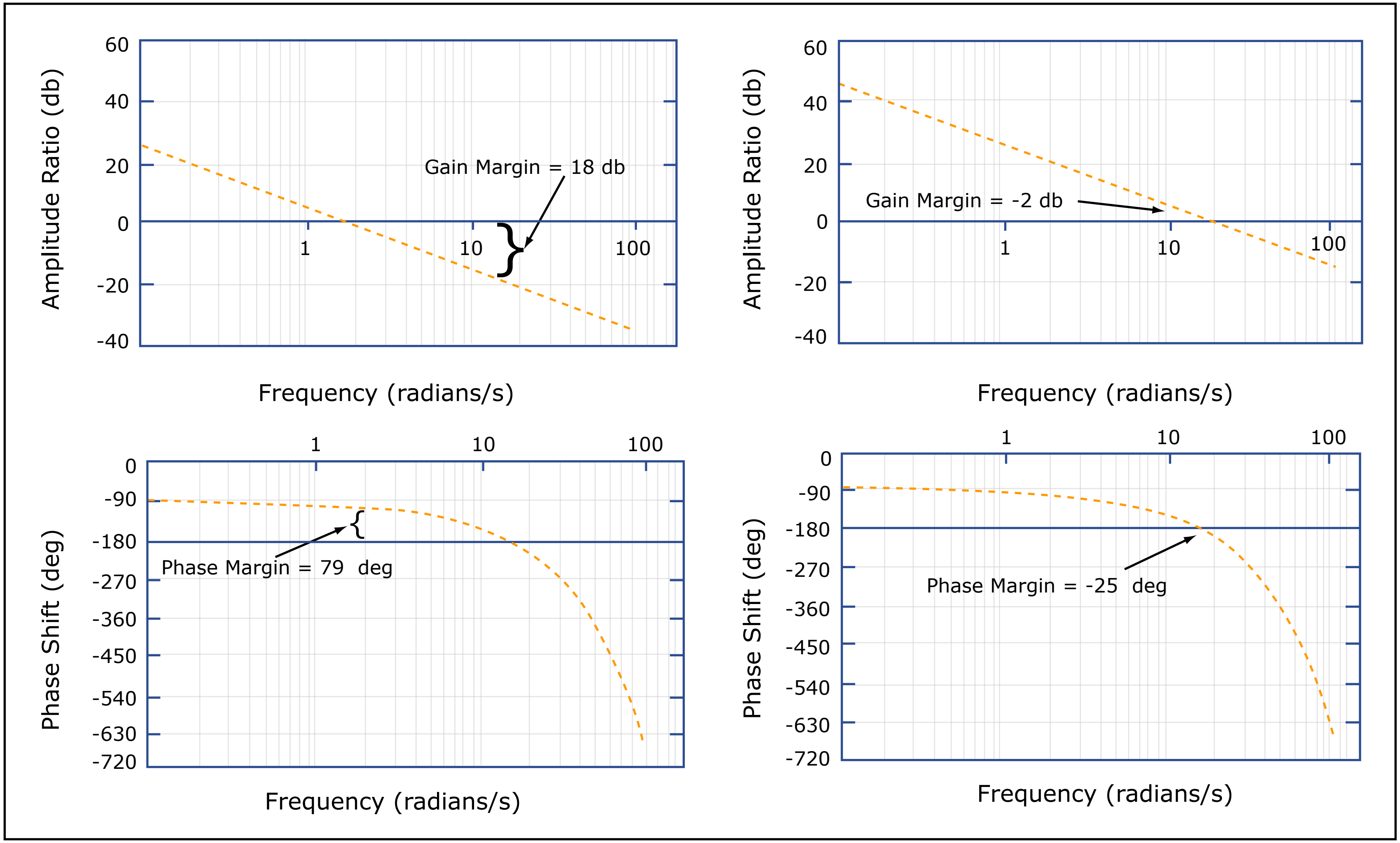
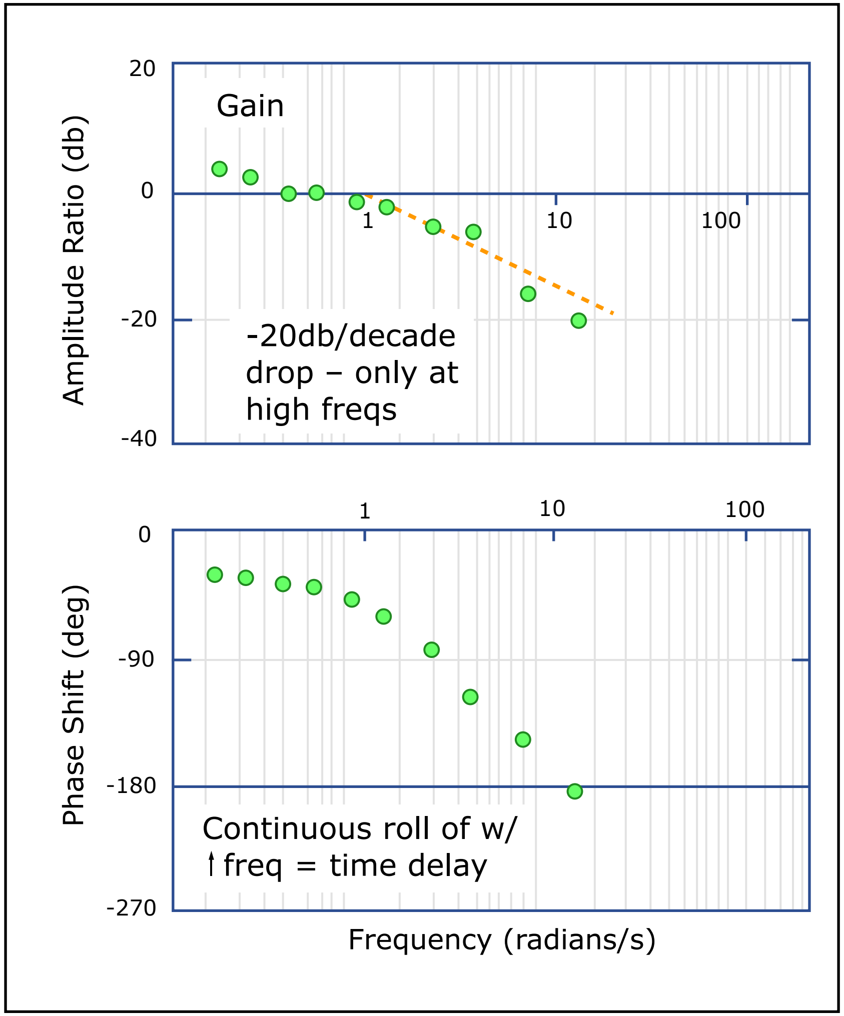


Image by MIT OpenCourseWare.

Operator Characteristics

0th order system

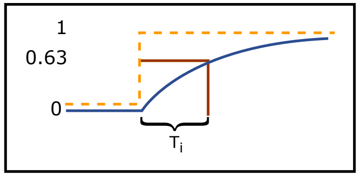


-20db/decade drop – only at high freqs

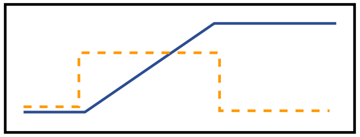
Continuous roll of w/ ↑ freq = time delay

Images by MIT OpenCourseWare.

- What can we say about this system in terms of the OLTF?
  - Gain
  - Time delay
  - Lag or integrator



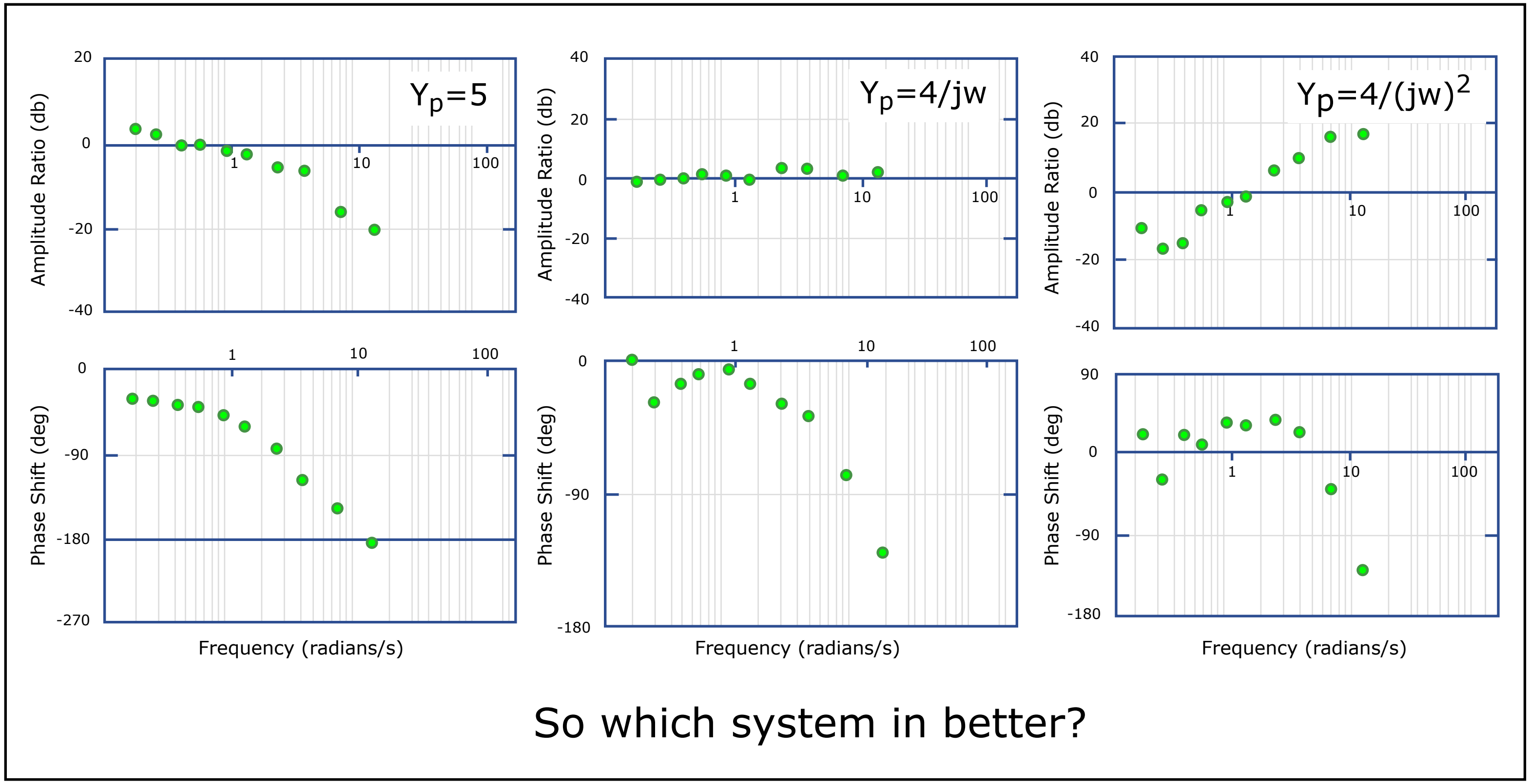
$$Y_H(j\omega)=\left[\frac{Ke^{-\tau jw}}{T_I j\omega+1}\right]$$



$$Y_H(j\omega)=\left[\frac{Ke^{-\tau jw}}{j\omega}\right]$$

Images by MIT OpenCourseWare.

One operator, three systems…



So which system in better?

Image by MIT OpenCourseWare.

0th order

Gain

Time delay

Integrator

1st order

Gain

Time delay

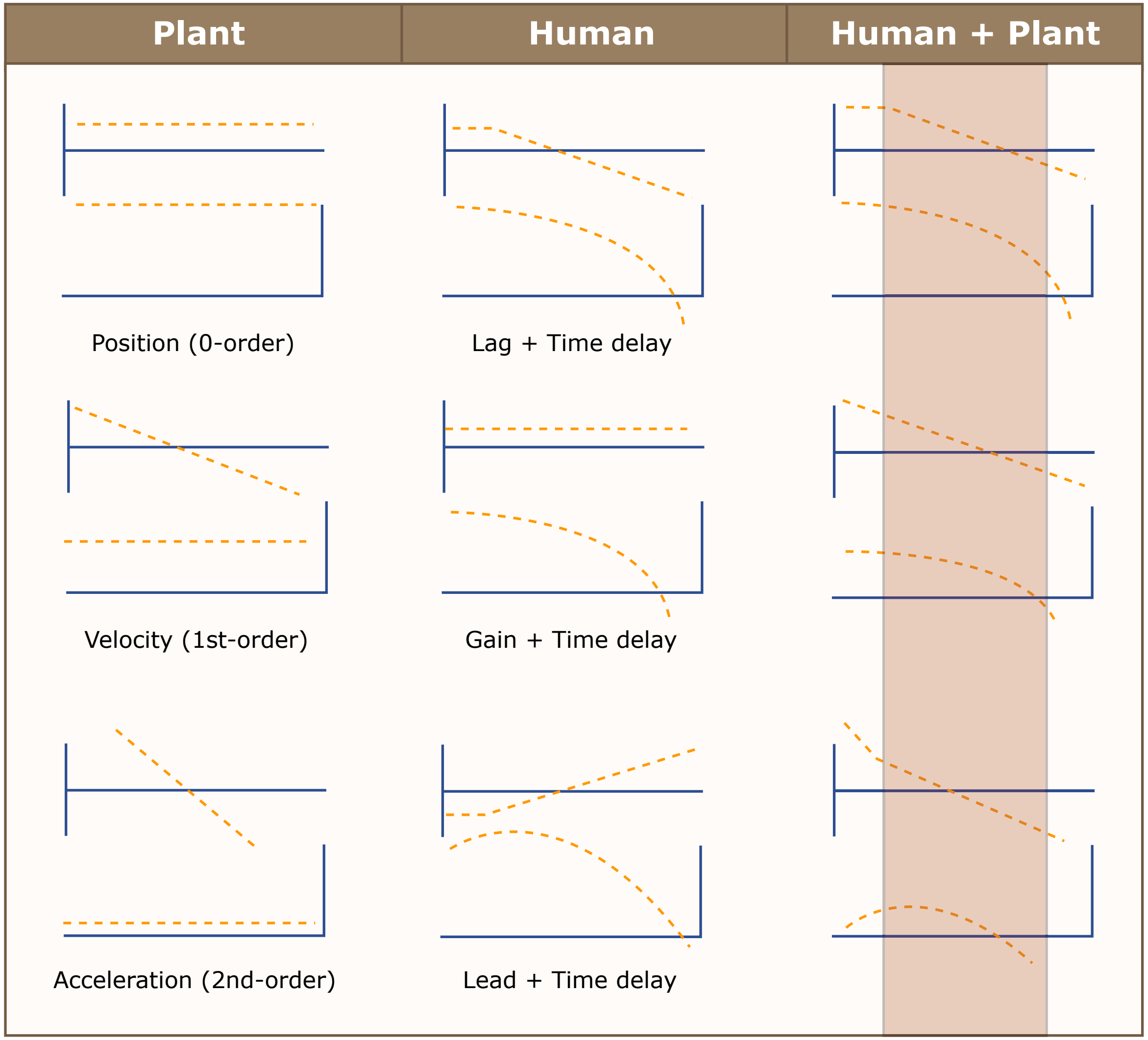
2nd order

Gain

Time delay

Lead at high freqs

Y_H is dynamic & adaptive



$Y_H Y_P$

Image by MIT OpenCourseWare.

Crossover Model

- McRuer, et al.
- Human and plant modeled as a team
- $Y_H Y_P$ looks like a gain, a time delay, and an integrator (first order system) in the region of ω_c
- Want (relatively) high gain so that errors can be fixed quickly but must be below 0db prior to phase lag of -180

$$Y_H(j\omega)Y_P(j\omega) = \frac{\omega_c e^{-\tau j\omega}}{j\omega}$$

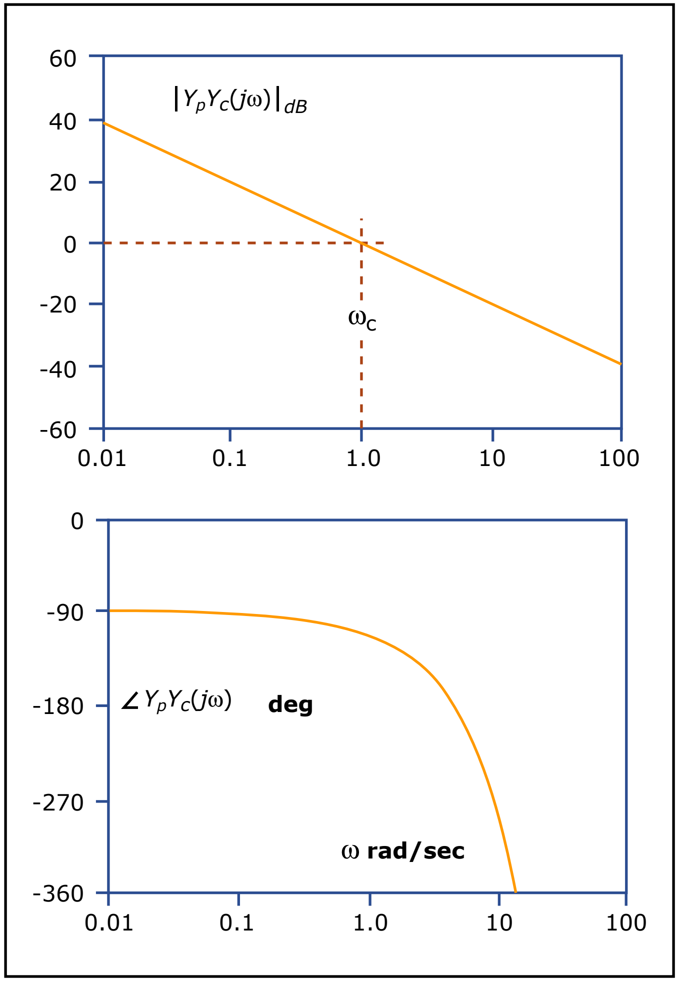


Image by MIT OpenCourseWare.

Crossover Model, II

Human Operator Limitations

$$Y_H(j\omega)=\boxed{\left[\frac{e^{-\tau j\omega}}{T_N j\omega+1}\right]}\boxed{\left[\frac{K(T_L j\omega+1)}{T_I j\omega+1}\right]}$$

<u>Numerator</u>

Information processing delay time: perception/cognition

<u>Denominator</u>

Action: Neuromuscular lag (< .2s)

Assumptions: Linearity & perfect attention

Model Strategic Parameters

Plant dependent:

- 0th order: Y_H is a apx. integrator/low pass filter
- 1st order: Y_H = pure gain
- 2nd order: Y_H is a differentiator

Crossover Model Results

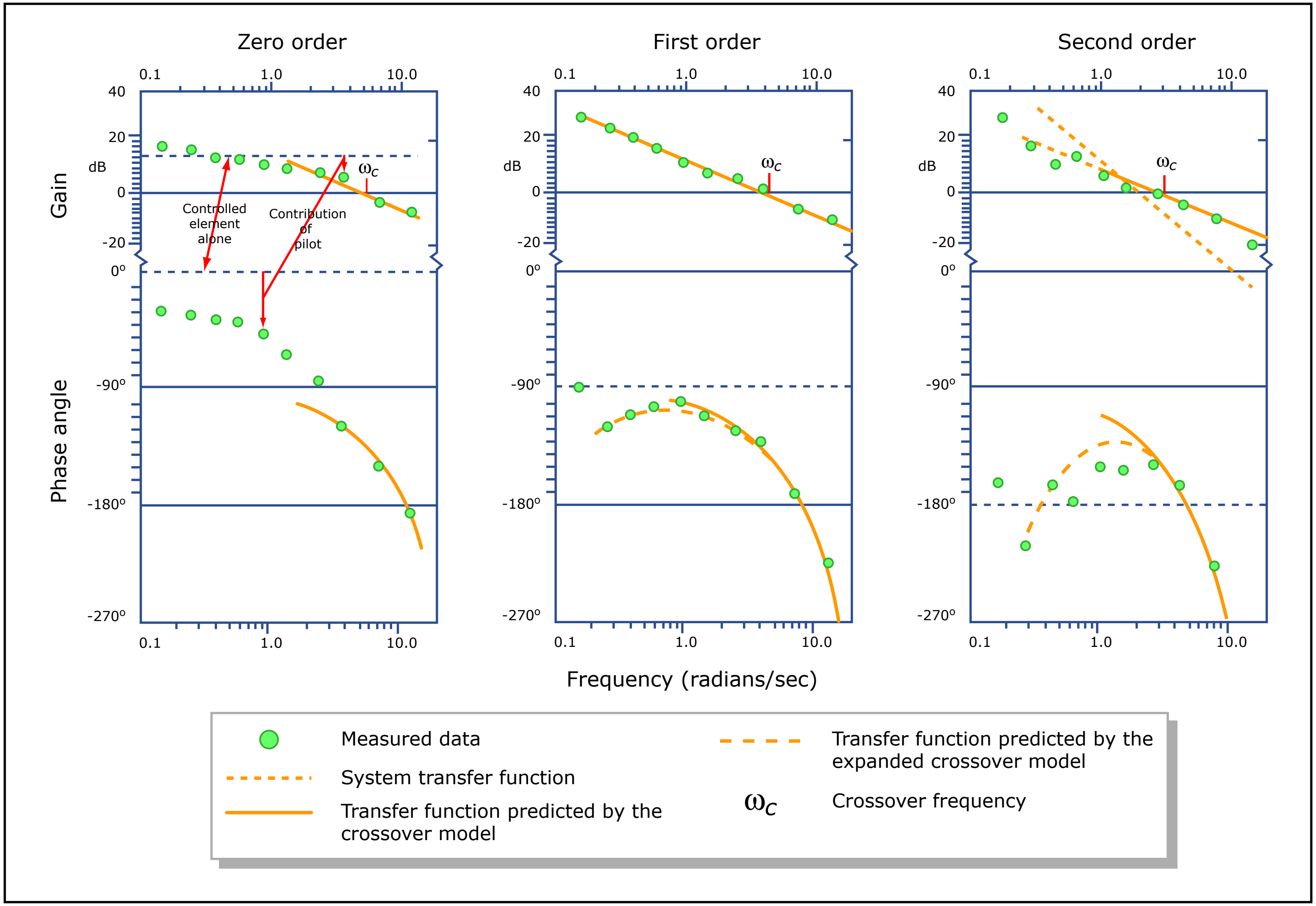


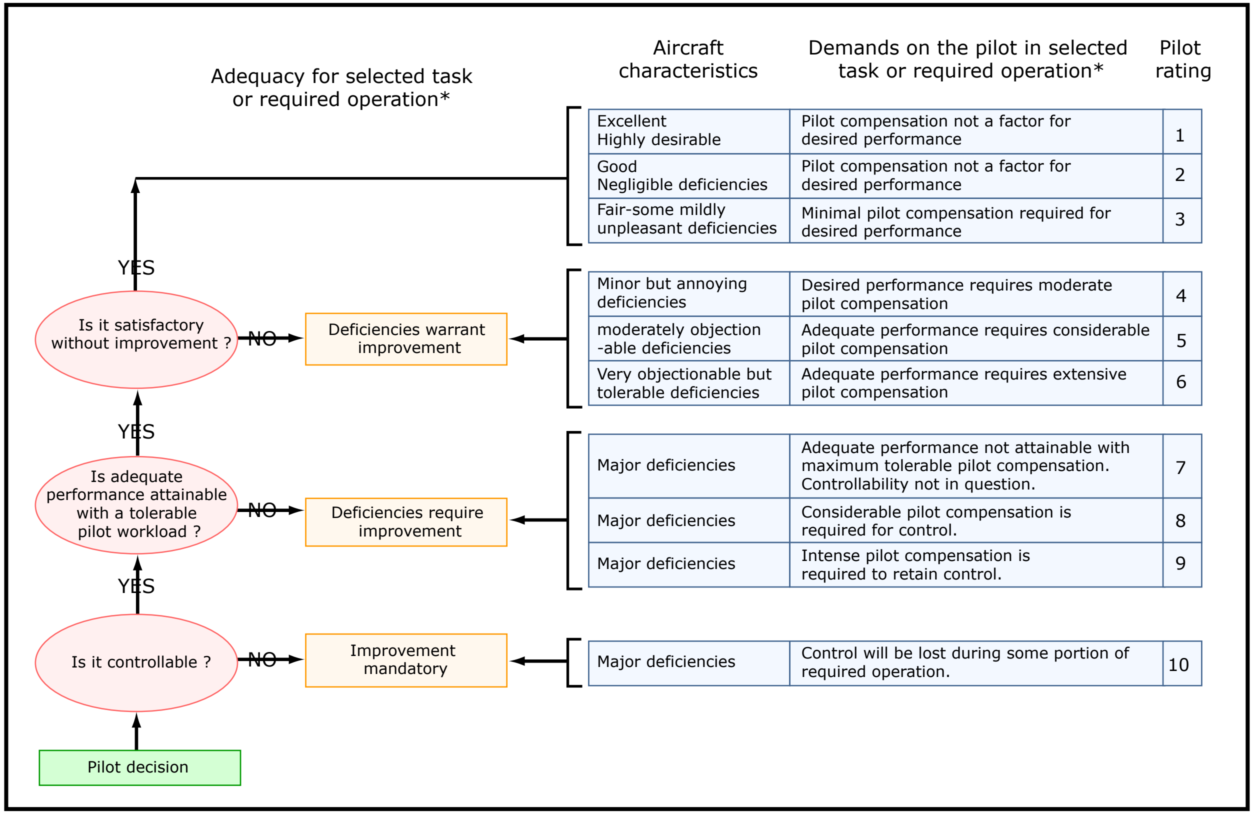
Image by MIT OpenCourseWare.

McRuer et. al (1967)

Subjective Pilot Feedback

- Pilots like gain
- Don’t like to have to generate lead
- Bottom line – 2nd order and higher systems are poorly rated (and for good reason)

Handling Qualities Rating Scale



Adequacy for selected task or required operation*

Pilot decision

Is it controllable ? NO → Improvement mandatory

YES

Is adequate performance attainable with a tolerable pilot workload ? NO → Deficiencies require improvement

YES

Is it satisfactory without improvement ? NO → Deficiencies warrant improvement

YES

Aircraft characteristics	Demands on the pilot in selected task or required operation*	Pilot rating
Excellent Highly desirable	Pilot compensation not a factor for desired performance	1
Good Negligible deficiencies	Pilot compensation not a factor for desired performance	2
Fair-some mildly unpleasant deficiencies	Minimal pilot compensation required for desired performance	3
Minor but annoying deficiencies	Desired performance requires moderate pilot compensation	4
moderately objectionable deficiencies	Adequate performance requires considerable pilot compensation	5
Very objectionable but tolerable deficiencies	Adequate performance requires extensive pilot compensation	6
Major deficiencies	Adequate performance not attainable with maximum tolerable pilot compensation. Controllability not in question.	7
Major deficiencies	Considerable pilot compensation is required for control.	8
Major deficiencies	Intense pilot compensation is required to retain control.	9
Major deficiencies	Control will be lost during some portion of required operation.	10

Image by MIT OpenCourseWare.

Optimal Control Model

- Crossover model limitations
  - Model & parameters are based on empirical data (essentially black box the human)
  - Cannot account for operator strategies, which are often dynamic

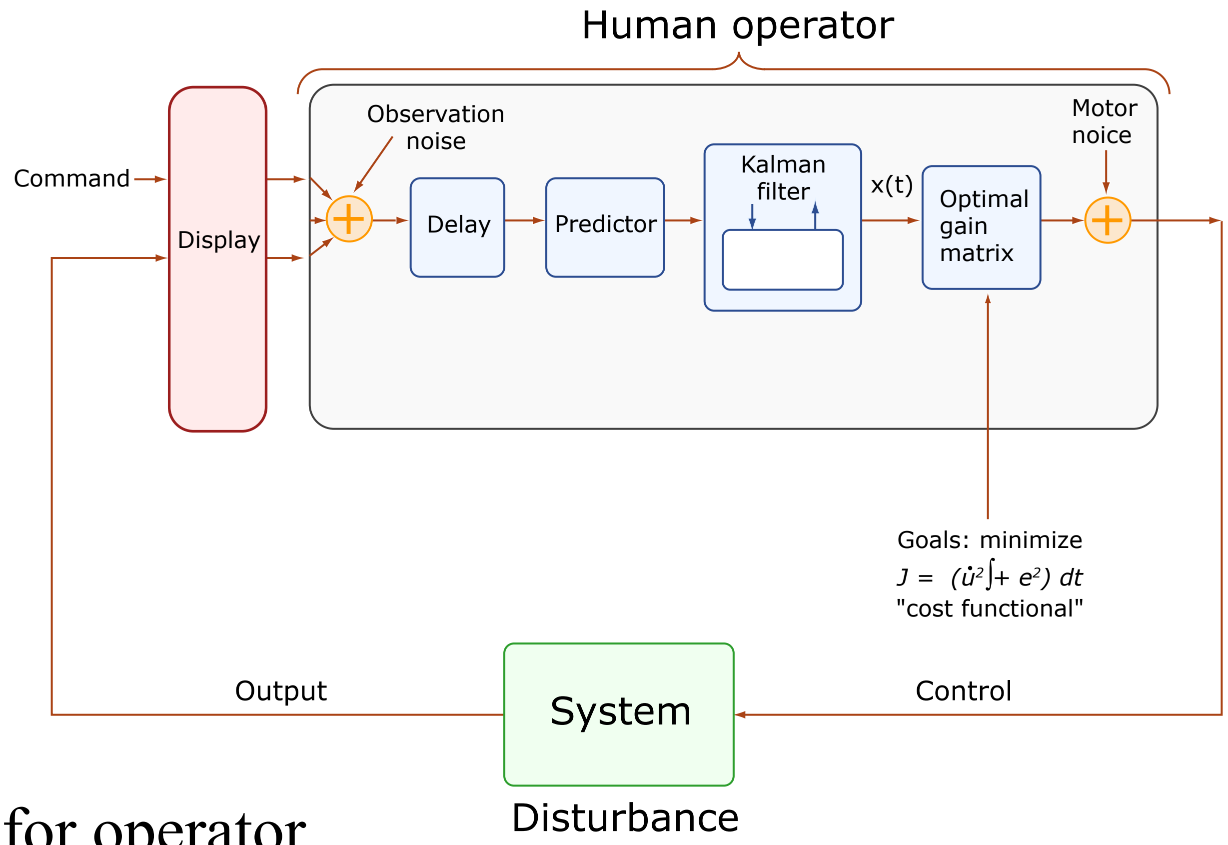


Image by MIT OpenCourseWare.

Optimal Control Model,, II

- Cost functional: $J=\int(Au^2+Be^2)\ dt$
  - u = control effort
  - e = control precision
  - A & B are adjustable weights
  - Cost benefit analysis by operator, e.g., smooth control vs. small error
- Two additional distinct operator states
  - Prediction
  - Estimation (Kalman filtering)
- Pros & Cons
  - Incorporates imperfect attention
  - Several parameters that must be adjusted to fit the data
  - PREDICTIVE MODEL BUILDING WARNING!!!

Human Structural Model

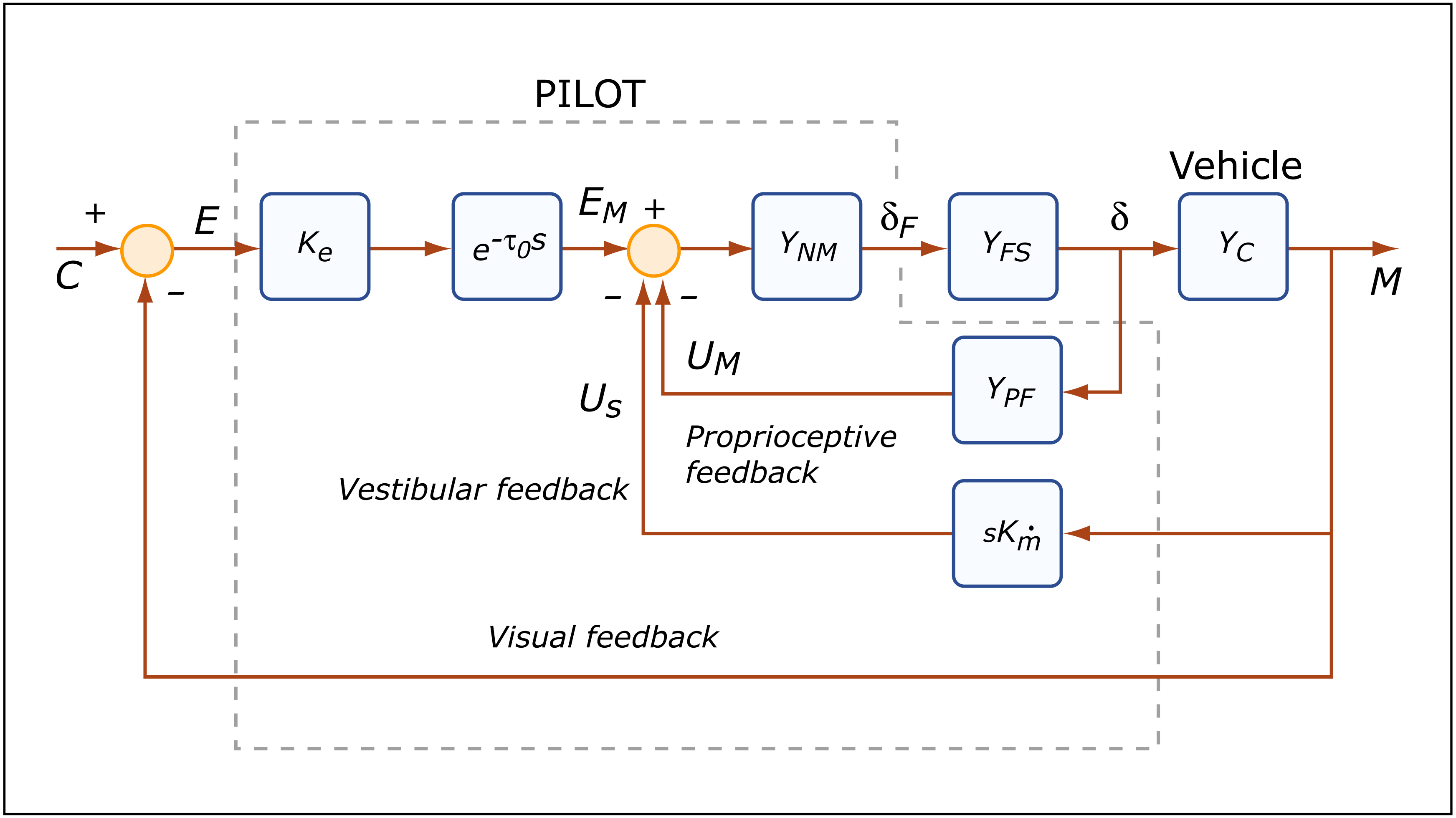


Image by MIT OpenCourseWare.

Hess, 1997

Multi-axis Control

- Cross-coupled & hierarchical tasks
- Lower order variables must be controlled to regulate higher order variables
- Cognitive workload & design interventions

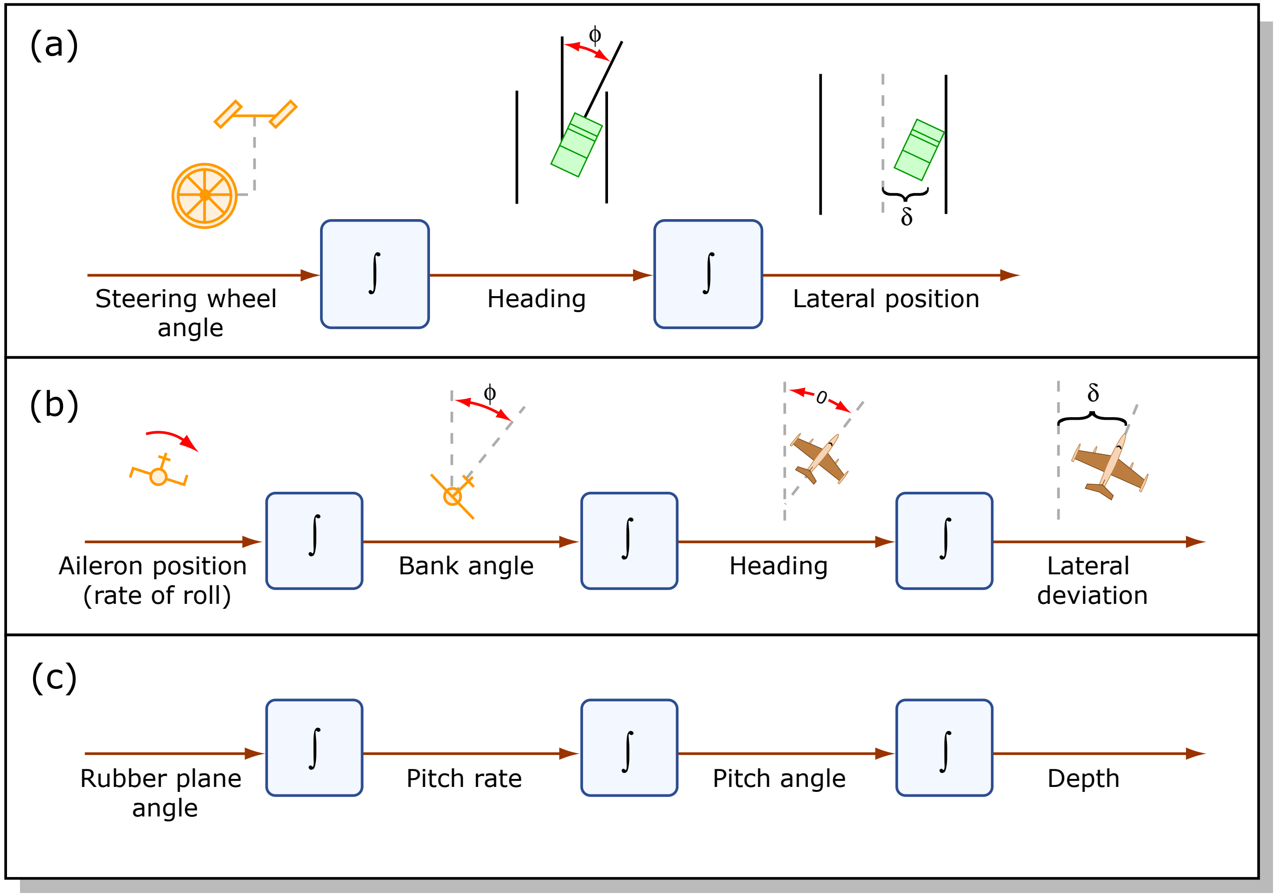


Image by MIT OpenCourseWare.

Inner Loop ⟷ Outer Loop

Multi-Axis Systems

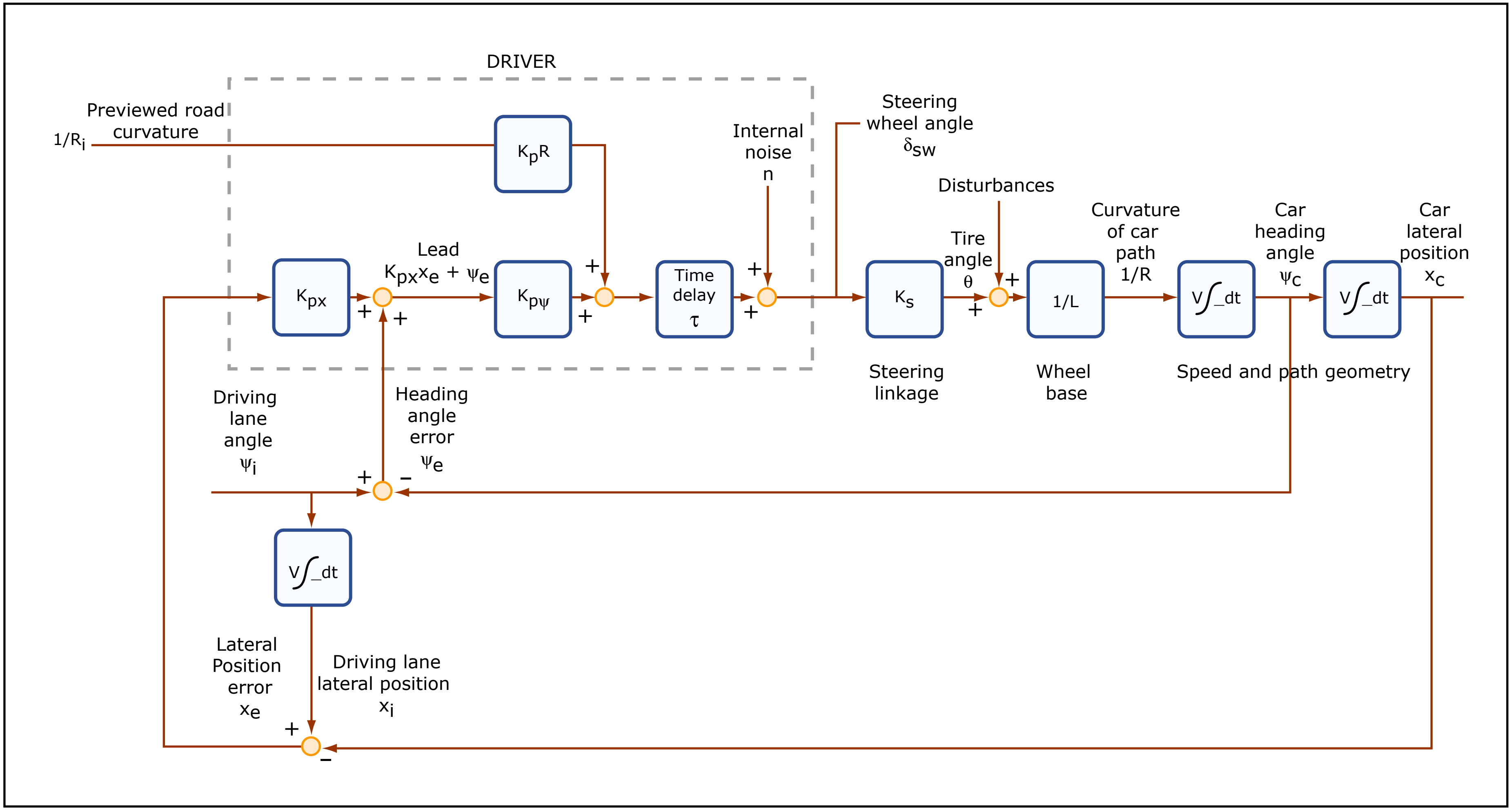


Image by MIT OpenCourseWare.

References

- McRuer, D. T., Krendel, E. S., & Reisener, W. (1965). *Human pilot dynamics in compensatory systems* (Wright-Patterson Air Force Base Technical Report, AFFDL-TR-65-15). NASA.
- *A Review of Quasi-linear Pilot Models*, Duane T. McRuer and Henry R. Jex, IEEE Transactions on Human Factors in Electronics HFE-3 (1967): 231-249.
- McRuer, D. T., & Krendel, E. S. (1974). *Mathematical models of human pilot behavior* (NASA Technical Report. AGARD-AG-188).
- Hess, R.A.: Unified Theory for Aircraft Handling Qualities and adverse Aircraft-Pilot Coupling, Journal of Guidance, Control and Dynamics, Vol. 20 No 6, 1997, pp. 1141-1148
- An optimal control model of human response Part 1: Theory and validation DL Kleinman, S. Baron and WH Levison: Automation 6 (1970): 357-368.

16.400 / 16.453 Human Factors Engineering
Fall 2011