Flight Control Fundamentals for Enabling Safe Flight of Quiet, Near-VTOL Personal Flying Vehicles

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GoFly Master Lecture
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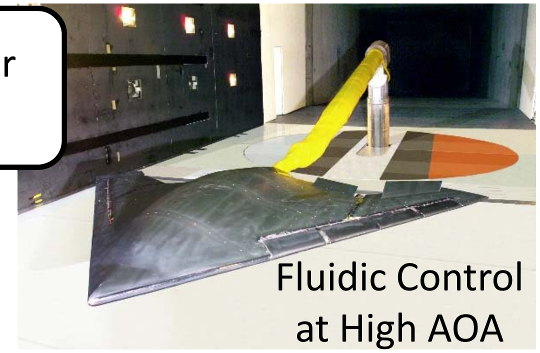
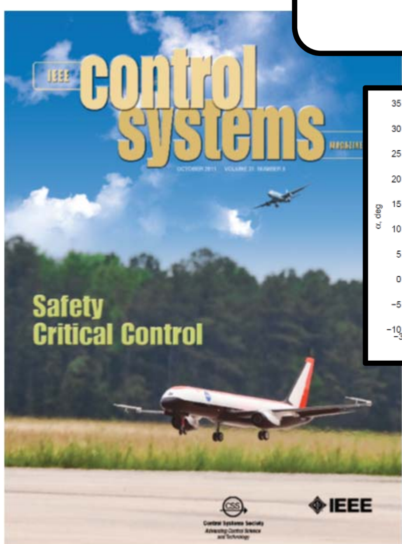
Introduce Your Presenter

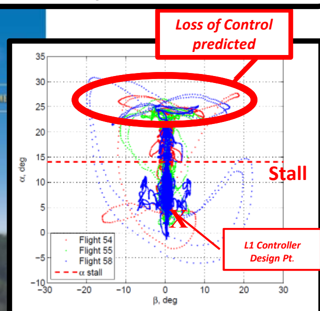
Dynamic Inversion for Highly Flexible Vehicles

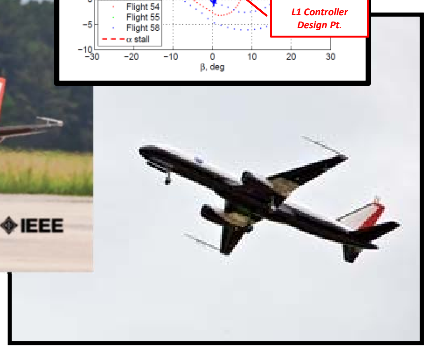
Fluidic Control for High AOA Flight



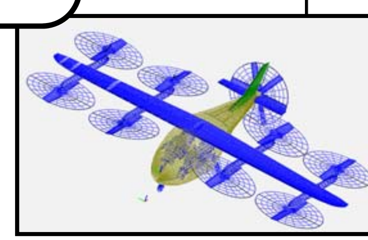
L1 Adaptive Control for Safety Critical Systems







Autonomous Vehicle Intelligent Contingency Management



Outline

- Introduction
- Control for Autonomous Flight
- Vehicle Dynamics Modeling and Simulation
- Fundamentals of Flight Control
  - Analysis and Design
    - Performance Specifications
    - Performance vs Robustness Tradeoffs
    - Robust Performance
    - Robustness to faults/failures
- Control Architecture and Typical Methodologies
  - PID
  - Loop shaping
  - LQR
  - Dynamic Inversion
  - Adaptive Control
- References

Flight Control Functional Decomposition – Autonomous Flight

Vehicle Management System

- Preflight System Diagnostic
- Flight plan/trajectory generation
- Mission management
  - Incorporation of sensor data
  - Assessment of vehicle capability
  - Decision making about continuing nominal mission
- Intelligent Contingency management
- Guidance
- Navigation
- Trajectory following control

What is Control?

- The term *control* has many meanings and often varies between communities
- Define *control* to be the use of algorithms and feedback in engineered systems to alter system behavior
- Feedback control is the basic mechanism by which systems, whether mechanical, electrical or biological, maintain their equilibrium..*
- At its core, control is an *information* science and includes the use of information in both analog and digital representations
- Control includes such examples:
  - feedback loops in electronic amplifiers,
  - “fly-by-wire” systems on aircraft
  - router protocols that control traffic flow on the Internet
  - high-confidence software systems
  - autonomous vehicles and robots
  - real-time resource management systems
  - biologically engineered systems

* from Chapter 1: Introduction to Modern Control Theory Lewis, F. L., *Applied Optimal Control and Estimation*, Prentice Hall, 1992.

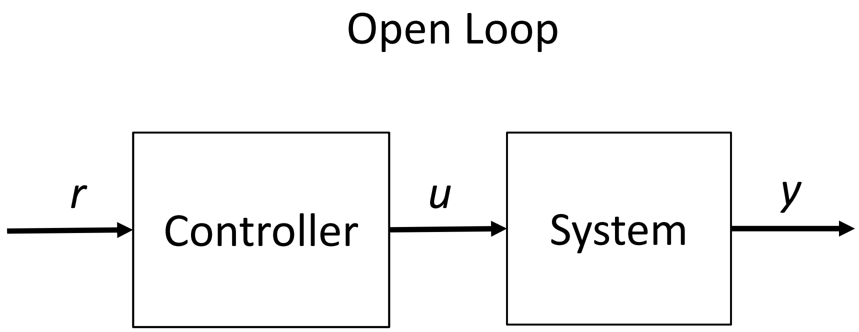
Control System

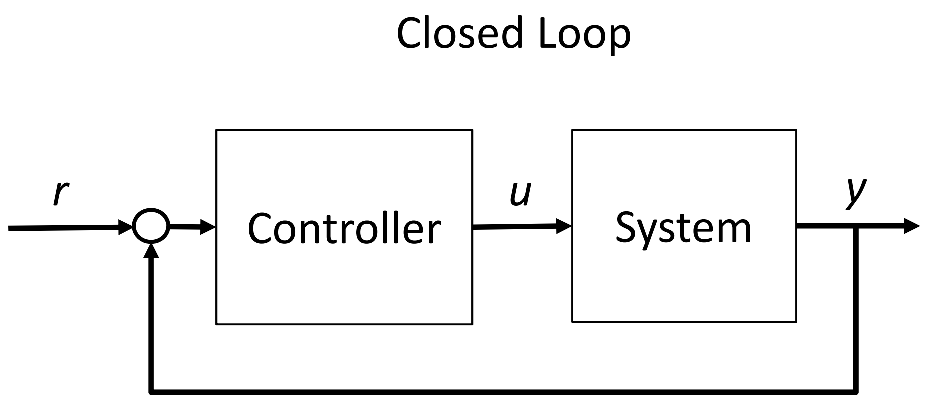
- A *modern controller* senses the operation of a system, compares it against the desired behavior, computes corrective actions based on a model of the system's response to external inputs and actuates the system to effect the desired change.
- This basic *feedback loop* of sensing, computation and actuation is the central concept in control.
- The key issues in designing control logic are ensuring that the dynamics of the closed loop system are stable (bounded disturbances give bounded errors) and that they have additional desired behavior (good disturbance attenuation, fast responsiveness to changes in operating point, etc.)
- These properties are established using a variety of modeling and analysis techniques that capture the essential dynamics of the system and permit the exploration of possible behaviors in the presence of uncertainty, noise and component failure.

Vehicle Dynamics, Modeling and Simulation

- Model the system to understand and control its behavior
- What if I don't have a vehicle model simulation but I can still fly it?
  - Can fly in a very narrow range
  - Do NOT know when the system would go unstable or would instability be controllable → catastrophic failure
    - Winds, mass shift, commanded inputs, ….
- Determine vehicle dynamics
  - Wind tunnel, computational experiments, i.e. CFD,
- Create vehicle simulation with standard equations of motion, models of vehicle subsystems, and incorporating vehicle dynamics
  - Models can be of variable fidelity, depending on availability and vehicle development stage
    - 1^{st} order transfer function for aerodynamic control surface that is fast compared to vehicle dynamics is sufficient, but need a more complex nonlinear model for an electric motor for propulsion system response
  - Update the vehicle model and its individual components as higher fidelity information becomes available from bench test, system identification during flight envelope expansion, …
- Use vehicle simulation to
  - design and analyze control laws
  - predict vehicle behavior for envelope expansion (stability, change in c.g., response to winds)

Why Feedback?

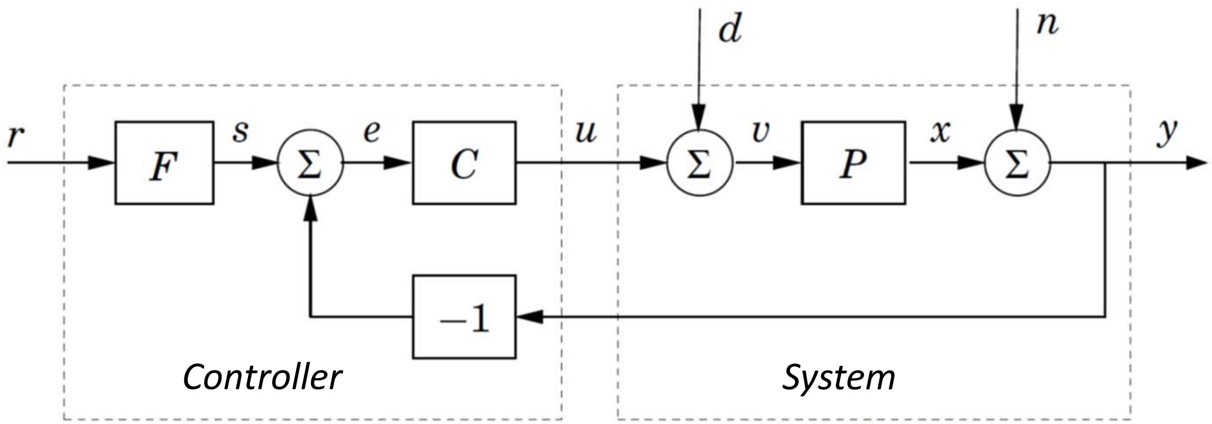




- If know system dynamics perfectly → open loop controller will perfectly track reference command, *y*=*r*
- Do NOT know system dynamics perfectly and have external environmental disturbances → need feedback to deal with error between reference command *r* and system response *y*.

Goal: Stability, Performance, Robustness

Feedback System



- Controller: feedback *C*, feedforward *F* (Controller with 2 degrees of freedom)
- Plant *P*: physical system including sensors and actuators
- Disturbance *d*: Drives the system from desired state
- Measurement noise *n*: Corrupts information about state *x*
- Plant variable *x*: should follow reference *r*

Assume *F=I,* focus on 1 degree of freedom system

Properties of Feedback

- Robustness to Uncertainty
- Generally, feedback allows a system to be insensitive both to external disturbances and to variations in its individual elements
  - Can also be used to create linear behavior out of nonlinear components (a common approach in electronics)
  - Reducing uncertainty is one of the main reasons for using feedback
- Design of Dynamics
  - Use of feedback is to change the dynamics of a system
    - Through feedback, we can alter the behavior of a system to meet the needs of an application: systems that are unstable can be stabilized, systems that are sluggish can be made responsive and systems that have drifting operating points can be held constant.
- Potential disadvantages:
  - Can create dynamic instabilities in a system, causing oscillations or even runaway behavior
  - Can introduce unwanted sensor noise into the system, requiring careful filtering of signals (especially in engineering systems)
- It is for these reasons that a substantial portion of the study of feedback systems is devoted to *developing an understanding of dynamics* and a *mastery of techniques in dynamical systems*

No Free Lunch → There is always a tradeoff

Feedforward

- Feedback is reactive: there must be an error before corrective actions are taken
- *Feedforward* is particularly useful in shaping the response to command signals
  - feedforward attempts to match two signals → requires good system models
- Experience indicates that it is often advantageous to combine feedback and feedforward
- Correct balance requires insight and understanding of their respective properties

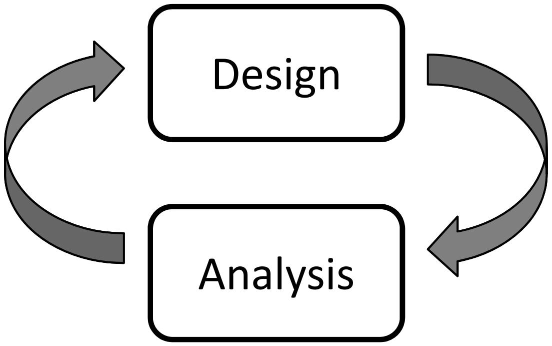
Criteria for Controller Design

General Design Procedure:

- Design controller *C* to achieve:
  - Low sensitivity to disturbances *d*
  - Low sensitivity and small injection of measurement noise *n*
  - High robustness to system variations, i.e. uncertainty and variability in plant dynamics
- Then design feedforward controller *F* to achieve desired response to command signal *r*

Control theory provides a rich collection of techniques to:

- design controller both in time domain and frequency domain,
- analyze the stability and dynamic response of complex systems, and
- place bounds on the behavior of such systems by analyzing the gains of linear and nonlinear operators that describe their components.



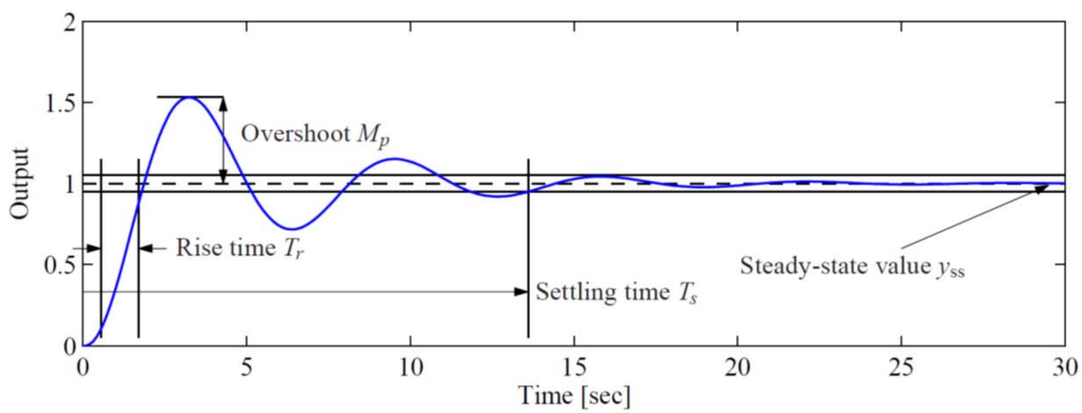
Stability, Robustness, Performance

- **Stability: bounded inputs produce bounded outputs**
  - Necessary and sufficient condition
  - Nonzero solutions around feedback loop
  - Basic problem: positive feedback (internal or external)
- **Performance: achieve desired response**
  - Specify performance in terms of frequency response
  - Main problems: disturbance rejection, command following
- **Robustness: stability/performance in the presence of unknown dynamics**
  - Check for stability in presence of uncertainty
  - Need to check stability for a *set* of systems

No uncertainty => No need for feedback

Focus on Analysis

- Neglect following the reference signal *r* and focus on the feedback problem, i.e. designing controller C with *F=I*
- Controller analysis must consider both performance, typically specified in time domain, and robustness, typically specified in frequency domain.



Rise time, overshoot, settling time and steady-state value → key performance properties

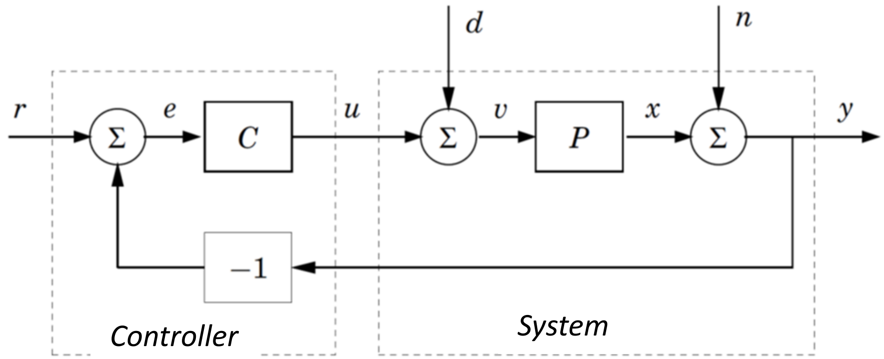
- There are relationships between time and frequency domain, e.g.
  - Rise time is related to system bandwidth, $\omega_c \sim {}^{1}/_{T_{rise}}$ where ω_c is a crossover frequency
  - Overshoot and settling time to system damping and frequency
- Focus on analysis in frequency domain

Frequency Domain Analysis

- Frequency response one of the key ideas that formed the foundation of control
- Focus on transfer function of a linear SISO system, equivalent analysis for MIMO systems
- The idea of frequency response is to characterize a linear time-invariant system by its response to sinusoidal signals
  - an alternative way of viewing dynamics (possible to deal with systems of very high order)
  - essential when discussing sensitivity to process variations
- Frequency response also gives a different way to investigate stability
  - a linear system is stable if the characteristic polynomial has all its roots in the left half plane.
  - derive the characteristic equation of the closed loop system and determine if all its roots are in the left half plane.
  - not easy to determine how the roots are influenced by the properties of the controller. It is for example not easy to see how to modify the controller if the closed loop system is stable.
- The way stability has been defined as a binary property, a system is either stable or unstable. In practice it is highly desirable to have a notion of the degrees of stability.
- The key is Nyquist's stability criterion which is a frequency response concept.

Closed-Loop Analysis

- Taking advantage of the idea of transfer function, i.e. system input/output representation and the Laplace transform, we derive simple rules for system analysis:



  - Derive transfer function for each block
  - Use algebra to obtain the transfer functions that relate the signals of interest.
  - Interpret the transfer function.
  - Simulate the system by computing responses to interesting signals.
- Transfer functions of interest:

$$Y(s) = \frac{PC}{1+PC}R(s) + \frac{P}{1+PC}D(s) + \frac{1}{1+PC}N(s)$$

- Loop transfer function:

$$L(s) = 1 + PC(s)$$

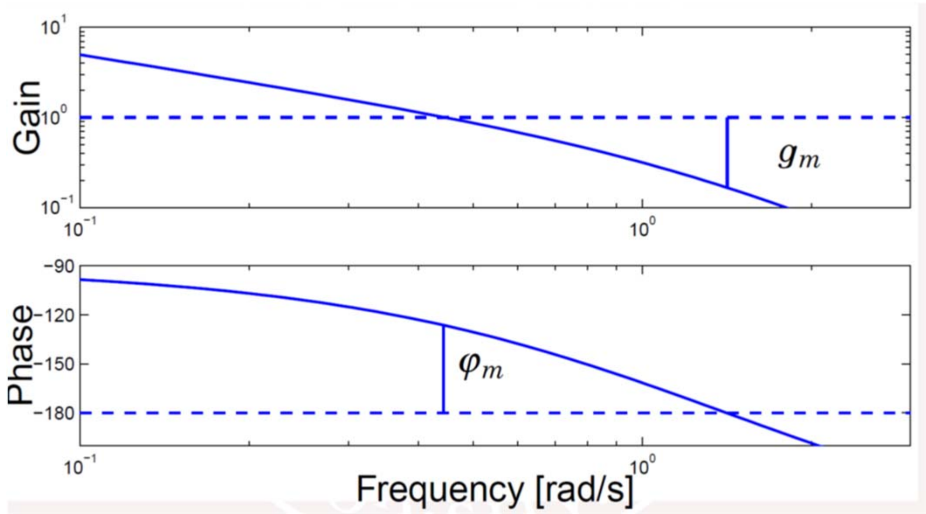
Closed-Loop Analysis - Stability

- Interested in margins of stability → this is governed by evolution of the loop transfer function $L(j\omega)$ $as\ \omega \to \infty$
- Stability margins are directly related to the gain and phase of $L(j\omega)$
- Useful representation is a Bode plot - two curves, the gain and the phase on logarithmic scale
- Introduce the concept of gain margin and phase margin
- gain margin g_m → how much the controller gain can be increased before reaching the stability limit
- phase margin ϕ_m → amount of phase lag required to reach the stability limit

Reasonable margins:

$g_m = [2, 5]$

$\phi_m = [30^\circ, 60^\circ]$



$$g_m = \frac{1}{|L(j\omega_{pc}|}$$

$$\phi_m = \pi + argL(j\omega_{gc})$$

Sensitivity Function

- Sensitivity function: $S = \frac{1}{1+PC} = \frac{1}{1+L}$
- Complimentary Sensitivity: $T = \frac{PC}{1+PC} = \frac{L}{1+L}$

$$Y(s) = T(s)R(s) + S(s)(PD(s) + N(s))$$

- $T(s)$ governs system ability to track commands, i.e. performance, and $S(s)$ governs response to disturbances and noise amplification
- Condition for stability in relation to system dynamics variation

$$\left|\frac{\Delta P(j\omega)}{P(j\omega)}\right| < \frac{1}{|T(j\omega)|}$$

- Variations can be large for those frequencies where *T* is small and that smaller variations are allowed for frequencies where *T* is large
  - Typically commands are lower frequency and noise is high frequency. Disturbances can be lower frequency, e.g. constant wind, or higher frequency, e.g. turbulence. System dynamics we do not want to excite, i.e. unmodeled and structural dynamics, are typically higher frequency.

Constraints on Design

- Advantageous to have a small value of the sensitivity function *S*
- Small value of the complementary sensitivity *T* allows large system uncertainty
- Stability and Robustness to system dynamics variation

$$\rightarrow \quad \boldsymbol{S} + \boldsymbol{T} = \mathbf{1}$$

- *S* and *T* cannot be made small simultaneously → $S(j\omega)$ is typically small for small ω and close to 1 for large ω; $T(j\omega)$ is close to 1 for small ω and goes to 0 as $\omega \rightarrow \infty$

- Fundamental conservation law of Control (Bode Integral):

  "water-bed" effect → Sensitivity, $S(j\omega)$, can be decreased at one frequency at a cost of increase at another

  → Limitations on achievable performance

- Can *S* can be made small over a large frequency range? → Depends

Fundamental Performance Limitations

- How quickly a system can respond to changes in the reference signal?
- Some of the factors that limit the performance are
  - Measurement noise
  - Actuator saturation
  - System dynamics
- Fast response requires a controller with high gain → fast closed loop system
- But: *measurement noise* is amplified and fed into the system → high frequency variations in the control signal, potentially leading to saturation → high frequency variation in system response

→ *Measurement noise* and *actuator saturation* gives a bound on the high frequency gain of the controller and on the response speed

- May be severe limitations due to the *dynamical properties* of the system. This means that there are systems that are inherently difficult or even impossible to control
  - fast closed loop system is required to stabilize an unstable pole and that the response speed should be matched to the unstable pole
  - right half plane zero $s = z$ is similar to a time delay $T = 1/2z$ → limits achievable response time

Proportional-Integral-Derivative (PID) Control

- Standard version of PID controller:

$$u(t) = ke(t) + k_i \int_o^t e(\tau)d\tau + k_d \frac{de}{dt}$$

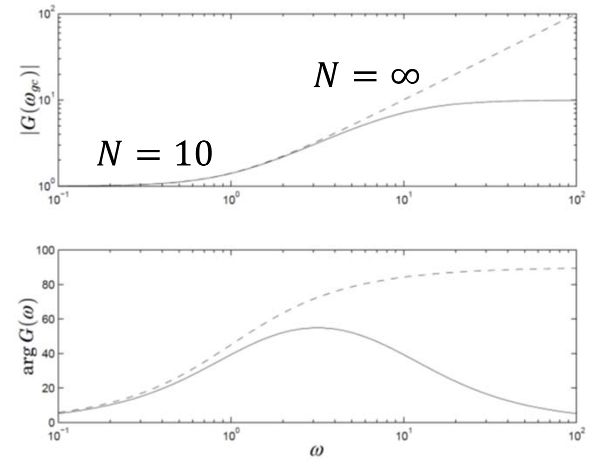
- where *u* is the control signal and *e* is the control error ($e = r - y$).
  - Proportional part acts on the present value of the error,
  - Integral represent and average of past errors, and
  - Derivative can be interpreted as a prediction of future errors based on linear extrapolation
- Practical Observations:
  - there is a large initial peak of the control signal, which is caused by the derivative of the reference signal → introduce weighting on reference signal *r* in proportional and derivative terms
  - implementation of pure derivative→ very noisy → derivative filtered by 1st order low-pass
  - Integrator anti-windup protection
- There are many ways to tune a PID controller.*
  - Traditional control techniques based on modeling and design – e.g. Pole placement: determine controller parameters → closed loop characteristic polynomial equal to specified polynomial

* Good starting references are by Astrom; a few are given in the reference section

Loop-shaping – Lead-Lag Controller

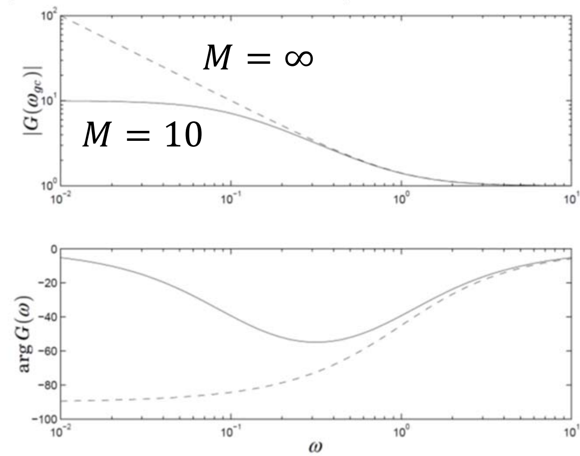
- Find a controller so that the loop transfer function has desired properties
  - Compensation is typically done by successive modifications of the loop transfer function starting with proportional control.
- Lead compensation used to improve the stability margin of a system or to increase the crossover frequency

$$C(s) = \frac{s+b}{s/_N + b}, \mathrm{N} > 1$$



- Lag compensation used to increase the gain of $L(j\omega)$ at low ω→ improve attenuation of low frequency disturbances and reduce error in tracking low frequency signals

$$C(s) = \frac{s+a}{s + a/_M}, \mathrm{M} > 1$$



- Closely related to PID

Linear Quadratic Regulator (LQR)

- Consider system dynamics model in state-space form: $\dot{x} = Ax + Bu, \; y = x$
- For a linear feedback, control signal $u = -Kx + K_r r$ results in closed-loop system $\dot{x} = (A - BK)x + BK_r r$

Controlling the system such that the performance index is minimal along all possible trajectories of the system is the *optimal linear regulator problem*.

$$J = \int_0^\infty \left[x^T(t)Qx(t) + u^T(t)Ru(t)\right]dt, \qquad Q = Q^T \geq 0, R = R^T \geq 0$$

- An optimal trajectory is generated by $u(t) = -Kx(t) \; \forall \geq 0, with \; K = R^{-1}B^T \, X$
  - Choose *Q* and *R* to be diagonal; balance relative penalties on state deviation and control effort
  - Tradeoff between attenuating disturbance and amplifying measurement noise by balancing deviation of state from zero and control effort

<u>Guaranteed</u> gain and phase margins at plant <u>input only</u>: (loop broken at plant input)

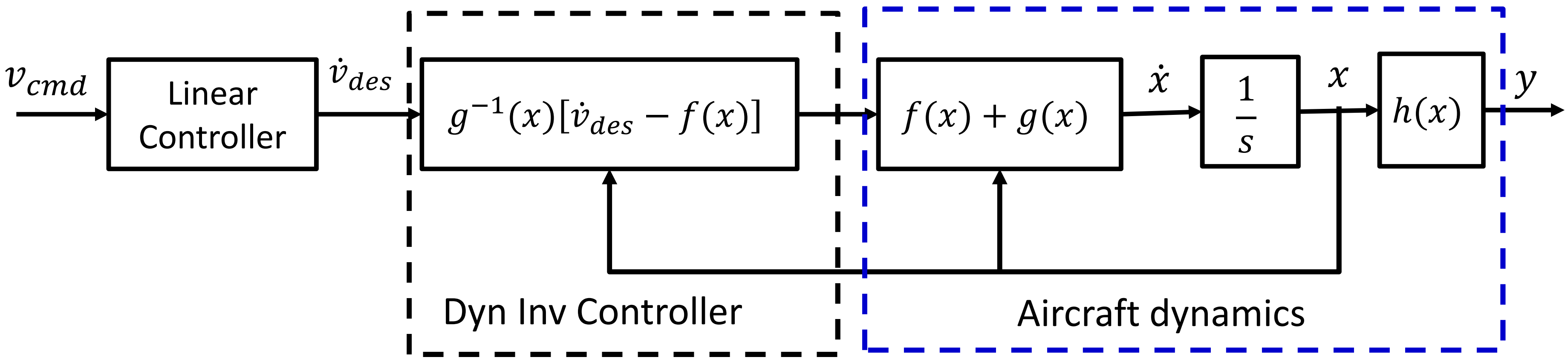
- Loop gain $L(s) = K(sI - A)^{-1}B$, for SISO case $|1 + L(j\omega)| \geq 1, \omega \in \mathbb{R}$

→ $\phi_m \geq 60°$

→ open-loop stable $g_m = [0, \infty]$, open-loop unstable $g_m = [1/2\,, \infty]$

Dynamic Inversion or Feedback Linearization

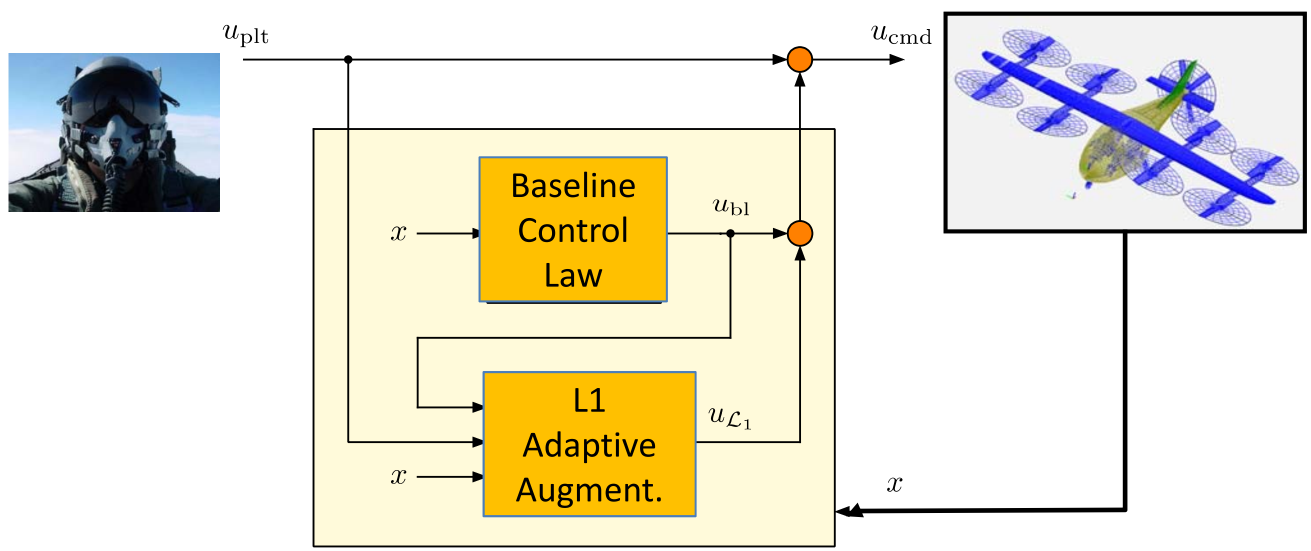
- Control of nonlinear systems; single linear control across the flight envelope
- Consider affine in control system: $\dot{x} = f(x) + g(x)u, \quad y = h(x)$
- Control action: $u = g^{-1}(x)\big(v - f(x)\big), where\ v = Control\ Variable\ of\ interest$
- DI is essentially a special case of model-following
- DI controller requires exact knowledge of model dynamics to achieve good performance
- Robustness issues play a significant role during the design process



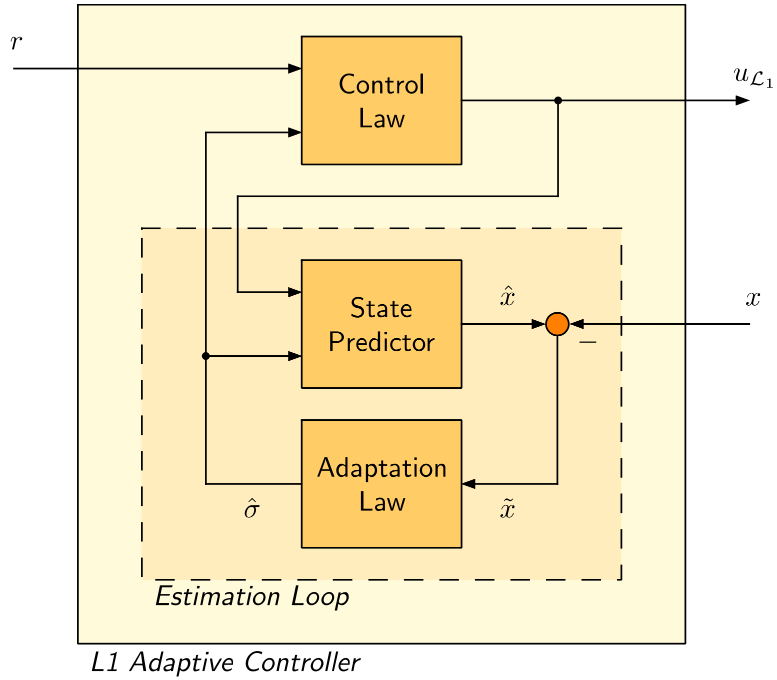
ideally => dynamic inversion controller + aircraft dynamics $\approx \frac{1}{s}$

Adaptive Control

- Dealing with varying model parameters, faults and failures → provides extra measure of robustness and safety is properly designed
- L1 Adaptive Control
  - method for the design of **robust adaptive control** architectures using **fast estimation schemes**
  - results in control architectures with *a priori* quantifiable **transient and steady-state performance specifications** and **robustness margins**
  - provides **systematic design guidelines** to solve the trade-off between performance, robustness, and adaptation
  - features have been **verified** – *consistently with the theory* – in a number of **flight tests** and **mid- to high-fidelity simulation environments**.



L1 Adaptive Control - Architecture



- An L1 adaptive controller consists of a **fast estimation scheme** and a **control law**.
- The fast estimation scheme includes a **state predictor** and an **adaptation law**, which together generate estimates of the uncertainties present in the system.
- Based on these estimates, the **control law** generates the control signal as the output of bandwidth-limited (low-pass) filter.

Summary

- Remember the tradeoffs between Performance and Robustness
- Design Challenges:
  - Disturbances
  - Measurement noise
  - System variations
  - System dynamics, time delays, RHP poles and zeros
  - Actuator performance and saturation
  - Sensor resolution and range
- Criteria for Control Design:
  - Attenuate effects of disturbances
  - Do not amplify measurement noise too much
  - Do not excite high frequency unmodeled dynamics
  - Make system insensitive to variation in system parameters
  - Make system state follow reference input
  - Make system robust to failures

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Thank you