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# Candidate Performance Metrics for Generalized Control for Autonomous Flight

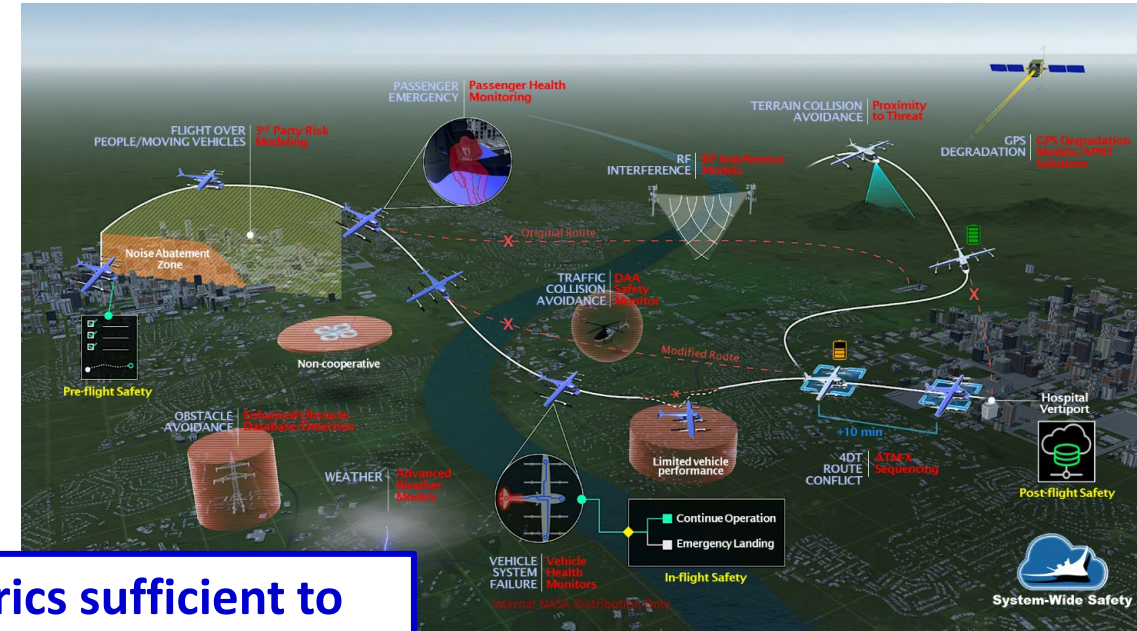
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# Motivation for Additional Metrics

- Emerging aerospace sectors – missions and vehicles
  - Autonomous cargo delivery
  - Urban Air Mobility (UAM)
  - Complexity of the environment
  - Proliferation of new vehicle configurations taking advantage of distributed electric propulsion – over actuated vehicles
  - Multi-modal dynamics - rotor-borne vertical takeoff/landing, fixed-wing lift phase between the two
  - Highly nonlinear flight dynamics - multiple propulsors, wings, and flight modes
  - Autonomous flight
- ➔ Tighter integration between flight control and trajectory planning, especially dealing with contingencies

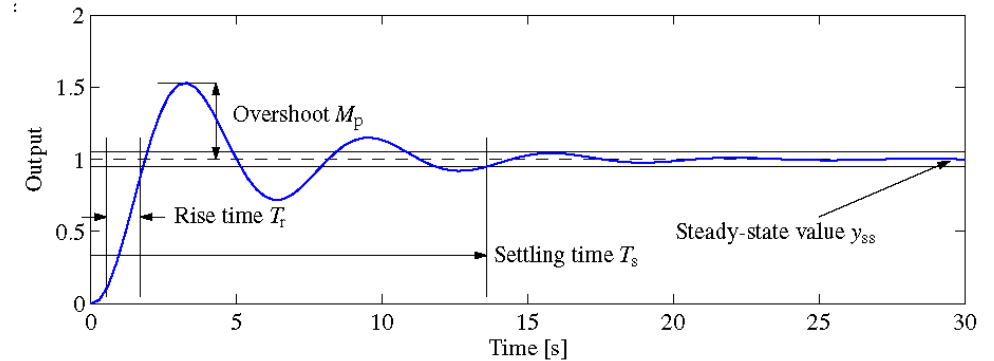
**Are current control metrics sufficient to operate safely and efficiently?**



# Current Metrics and Requirements

## Analysis problems:

Given a controller, determine if the **controlled signals** (including tracking errors, control signals, etc.) satisfy the **desired** properties for **all admissible noises, disturbances, and model uncertainties**.



Time domain performance specifications

- Requirements describing **linear** system performance and stability characteristics for fixed-wing and rotorcraft
  - MIL-STD-1797A - Flying Qualities of Piloted Aircraft (1995)
  - MIL-F-8785C - Flying Qualities of Piloted Aircraft (1980)
  - ADS-33E-PRF - Aeronautical Design Standard, Performance Specification, Handling Qualities Requirements for Military Rotorcraft



- Single Input Single Output (SISO), one loop at a time analysis
- Analysis at each equilibrium position for linearization
- Frequency based tools – Bode, Nyquist, Nichols
- Stability robustness - gain and phase margins (scalar analysis)
- Nonlinear simulation Monte Carlo to verify gain and time-delay margins (phase margin equivalent)



# Typical State-of-Practice Metrics

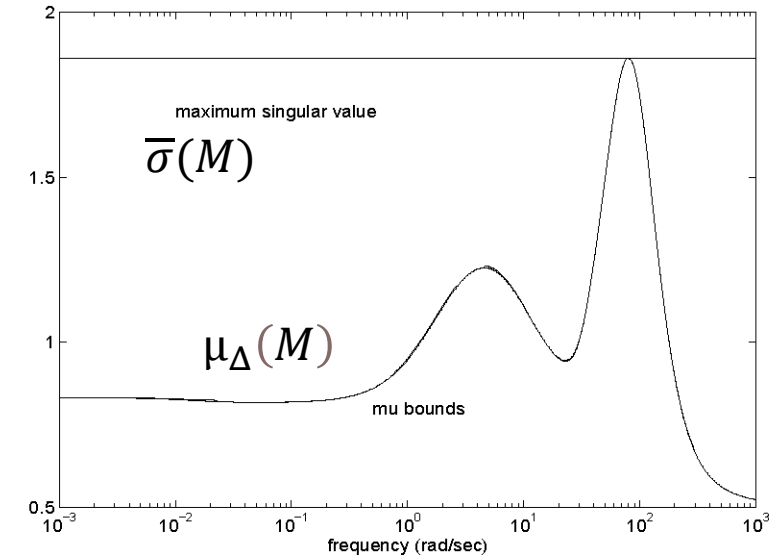
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- Multiloop systems (MIMO)
  - individual loops may be analyzed using SISO scalar techniques
  - but fail to capture the essentially multivariable nature of many systems, e.g. ignore variations simultaneously affecting multiple loops
- Main difference between a scalar (SISO) system and a MIMO system → presence of directionality
- Singular value decomposition (SVD) provides a useful way of quantifying multivariable directionality
  - a natural way it provides multivariable interpretation to many key classical control concepts
  - generalize the Bode and Nyquist techniques for multivariable systems
- Minimum singular value,  $\underline{\sigma}(A)$ , of  $\mathbf{A}$  → measure of how close  $\mathbf{A}$  is to being singular → robustness measure
- Degree of robustness of a MIMO system → how close to **singular** is the return difference matrix (computing  $\sigma_i$  vs.  $\omega$ )
  - used in forming a multivariable gain margin ( $\sim$  classical gain margin)
- Classical gain and phase margins → robustness of SISO systems to perturbations in the feedback loop
- Singular values → robustness of MIMO systems
- Directed Monte Carlo analysis → verify the results of linear analysis within uncertainty bounds in region of interest



# Additional Control Metrics - SSV

- System is subject to multiple sources of uncertainties →
- Reflect all sources of uncertainties from their known point of occurrence to a single reference location in the loop
  - reflected uncertainties invariably have a great deal of structure
  - “covered up” with a large, arbitrarily more conservative perturbation in order to maintain a simple bounded representation at the reference location
- Introduces significant conservatism to the analysis
- SSV is a powerful framework that removes conservatism associated with unstructured uncertainty and singular value analysis
- SSV provides a measure of "destabilizing" perturbation for a system with structured uncertainty
- SSV is proposed as an additional metric used for analysis of system robust stability and performance



$$\Delta = \{diag[\delta_1 I_{r_1}, \dots, \delta_s I_{r_s}, \Delta_1, \dots, \Delta_F] : \delta_i \in \mathbb{C}, \Delta_j \in \mathbb{C}^{m_j \times m_j}\}$$

$$\mu_{\Delta}(M) := \frac{1}{\min\{\bar{\sigma} : \Delta \in \mathbf{\Delta}, \det(I - M\Delta) = 0\}}$$



# Nonlinear System Challenge

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- New class of vehicle not well understood, rapidly changing designs.
- Dynamic nature of these systems less likely that analysis around fixed equilibria will sufficiently capture system performance
  - tilt-wing vehicle, stability at an arbitrary point during a wing-tilt transition is of less interest than ensuring that the entire transition maneuver is performed safely and robustly
- Dependence on the trajectory leads to two new design considerations →
  - the robustness of the system is dependent on how close the system state is to the designed trajectory
  - the trajectories from planners be compatible with the system dynamics
- The interplay between the levels of control must increase, guidance, control, sensor processing must all be considered together, rather than individually
- The interplay between the GNC systems and the dynamics must be a priori predictable
- Some metrics on system performance should be tied to specific trajectories or classes of trajectories

# Challenge to the Aerospace Community

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- Multi-modal vehicle dynamics, highly nonlinear during transition
  - Complex operating environment
  - Combination of likely contingencies
- Drive the need to establish additional generalized control metrics that can be evaluated in a practical manner and produce non-conservative results

Question of additional appropriate metrics that would quantify generalized control robust stability and robust performance is wide open



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# Questions?

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