Perspectives on Computation and Flight Control

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Princeton University

Aerospace Control and Guidance Systems Meeting,

October 2023, Newport News, VA

- Flight Testing
- Analysis & Computation
  - Stochastic Robustness
  - Nonlinear Dynamic Inversion
  - Air Traffic Management
  - Adaptive Neural Networks
- What's next?

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Digital Fly-By-Wire Control

- 1968: Apollo 7: Apollo Guidance Computer
  - First crewed DIGITAL FLY-BY-WIRE (DFBW) control system
- 1971: VTOL: X-14B, CRC Bell 205
- 1972: CTOL: NASA F-8 DFBW, Apollo AGC

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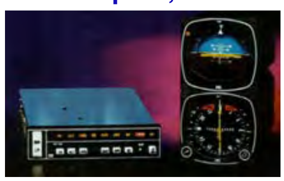
First DFBW in Series Aircraft

SAAB JA37 Viggen
DFBW, 1977

Airbus A320
DFBW, 1987

Bendix KFC 150
Autopilot, '90s



Dassault Falcon
7X DFBW, 2005

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Apollo Guidance Computer (AGC)

- 16-bit Processor
- Storage: 36,864 words (fixed)
- 2,048 words (erasable)
- Weight: 70 lb

- Clock speed: 1 MHz
- Digital Autopilot: 2,000 words

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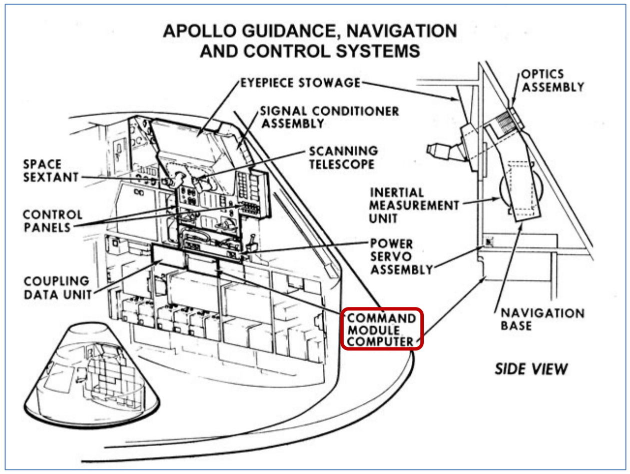
MIT Instrumentation/Draper Laboratory



- **Digital Autopilot Group Member, 1968-1973**

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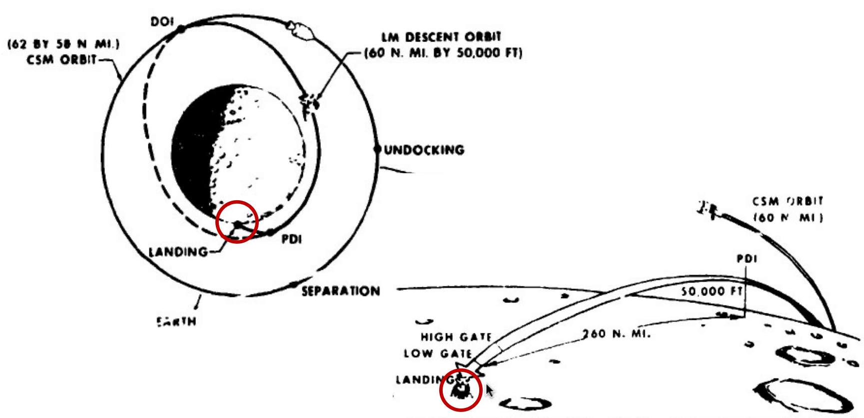
Lunar Orbit and Landing



PHASE	INITIAL EVENT	DESIGN CRITERIA
BRAKING	PDI	MINIMIZE PROPELLANT USAGE
APPROACH	HIGH GATE	CREW VISIBILITY
LANDING	LOW GATE	MANUAL CONTROL

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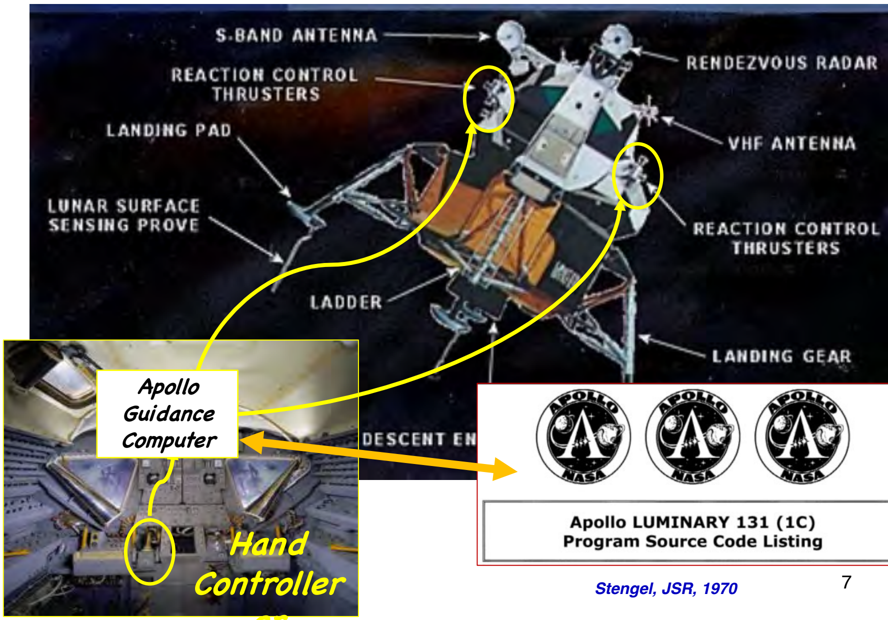
Lunar Module, Apollo 11, 1969



Apollo LUMINARY 131 (1C)
Program Source Code Listing

Stengel, JSR, 1970

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AGC Assembly Language

```
         CA       40CYC
         TS       TCP
         TC       PEGI
         CA       RCSFLAGS          CHECK FOR DIRECT RATE COMMAND LAST TIME.
         MASK     PBIT
         EXTEND
         BZF      +2
         TC       PEGI              TO PURE RATE COMMAND
         CA       DXERROR           PSEUDO-AUTO CONTROL.
         TS       E                 X-ATTITUDE ERROR (SP)
         TS       PERROR            LOAD P-AXIS ERROR FOR MODE1 FDAI DISPLAY
         TC       PURGENCY +4
PEGI     CA       CDUX              DIRECT RATE CONTROL.
         TS       CDUXD
         CA       ZERC
         TS       DXERROR
         TS       DXERROR +1
         TS       PERROR
         CCS      EDOTP
         TC       +3
         TC       +2
         TC       +1
         TS       ABSEDOTP
         AD       TARGETDB
         EXTEND
         BZMF     LAST
         CA       TCP
         EXTEND
         BZMF     LAST
         CS       RCSFLAGS
```

Apollo LUMINARY 131 (1C)
Program Source Code Listing

Neil Armstrong's remark on landing control: "AS ANTICIPATED, QUICK AND RESPONSIVE."

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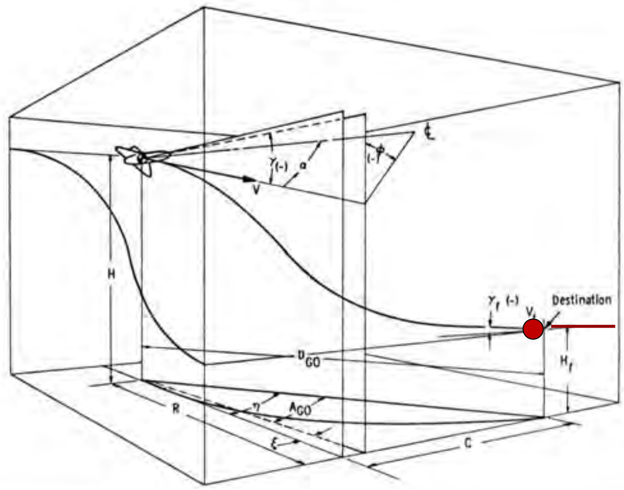
Prototype Optimal Guidance, Digital Autopilot for Space Shuttle



Stengel, JSR, 1971-74

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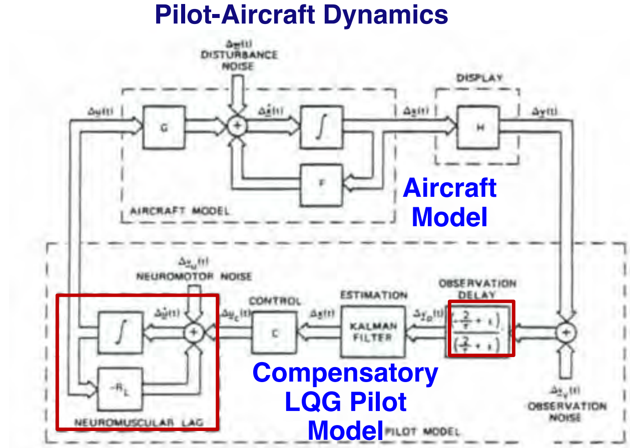
High-Angle-of-Attack Stability and Control*

The Analytic Sciences Corporation (TASC) [1973-1977]

Pilot-Aircraft Dynamics



Broussard, Stengel, IEEE TSMC, 1978
(after Kleinman, 1971)

* *ONR Contract*

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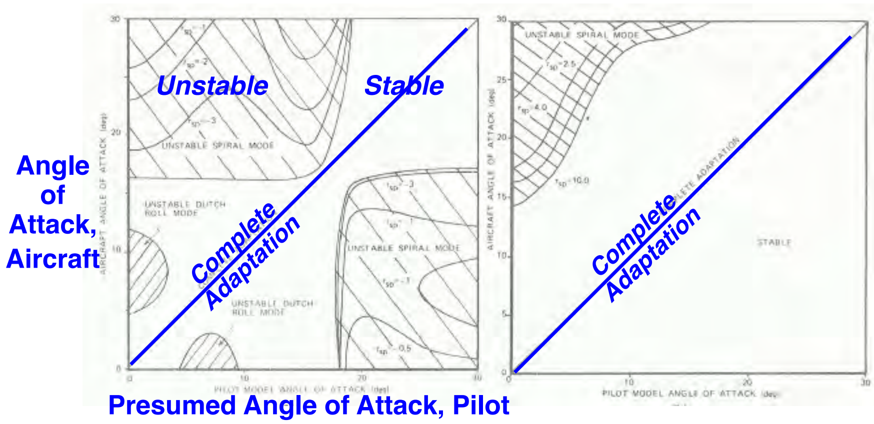
Pilot Adaptation in Wind-Up Turn (SAS/ARI Off)



Lateral Stick Alone *Lateral Stick + Pedals*

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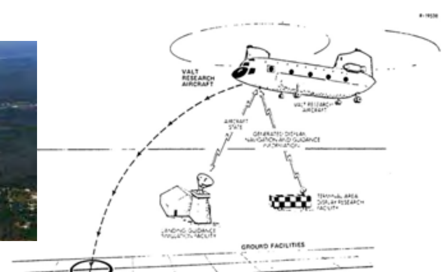
DFBW Design for NASA Vertical Approach and Landing Technology (VALT) CH-47B*



- Adaptive Linear-Quadratic-Gaussian Regulator
- Rolm 1666 computer
  - *16-bit, 64K, FORTRAN*
- Flat-screen display formatted in ground trailer; downlink/uplink

TASC: Broussard, Berry, Stengel, Automatica, 1978
NASA: Downing, Bryant, 1987

** NASA Contract*

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Flight Research Laboratory, 1977-1983

- ¼-acre hangar
- Princeton Forrestal Campus
- 3,000-ft runway
- Five aircraft, two with variable-stability systems

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Variable-Stability Navion Aircraft

- *3 controllable forces*
- *3 controllable moments*
- *Side-force panels*
- *Multiple backup modes*
- *0.5-g maximum side force*

=========

- *VRA w/o Side Force*
- *75-105 kt*

North American Variable-Response Research Aircraft (VRA), 6-DOF control

Ryan Avionics Research Aircraft (ARA), 5-DOF control

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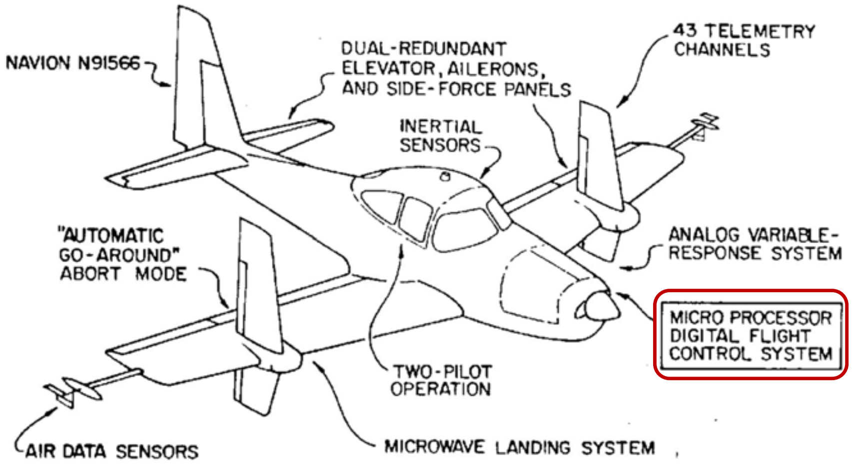
Variable-Response Research Aircraft (VRA)
(Modified *North American Navion A*)



Seat, Miller, Nixon, 1977-78

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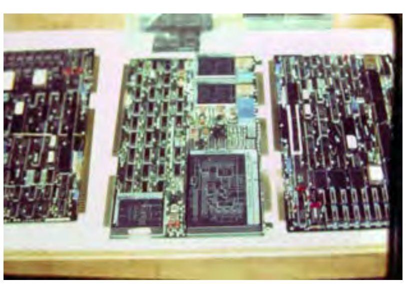
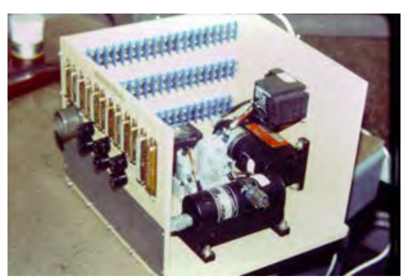
Digital Processor for Flight Control and Data Acquisition, 1978

- SBC 80/05 Multibus (8085 CPU), 8 bits, 6 MHz clock
- Amd9511 Floating Point
- A/D, D/A, and Memory
- 1st flown in 1978





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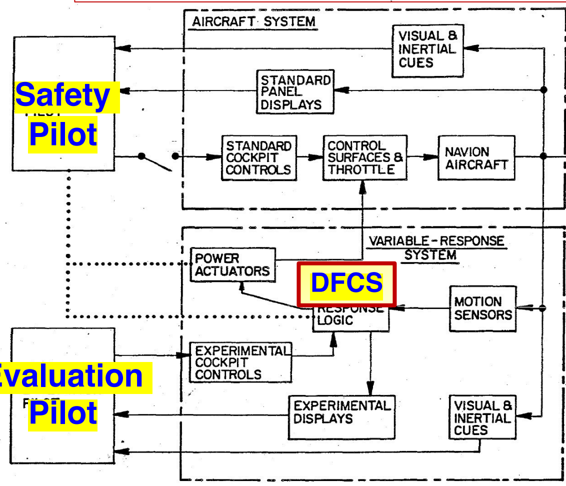
Princeton Variable-Stability System

- Safety Pilot and Test Conductor
- Evaluation Pilot



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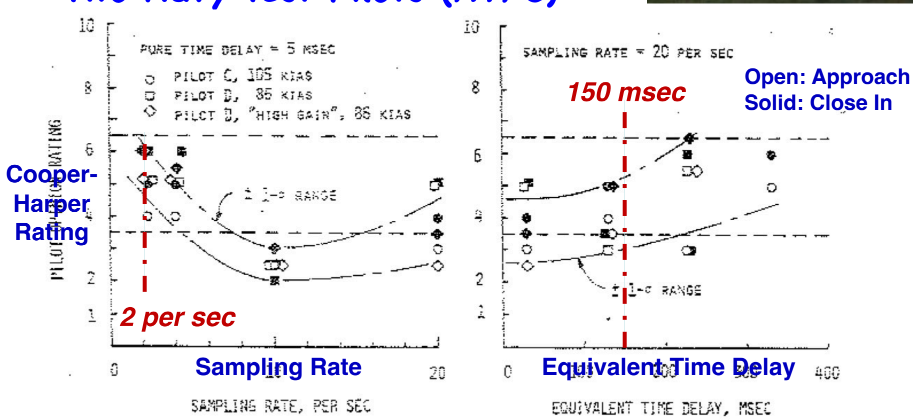
Evaluation of DFBW Sampling Rate and Pure Time Delay

- Field Carrier Landing Practice
- Two Navy Test Pilots (*NTPS*)



Stengel, Miller, JGC, 1979

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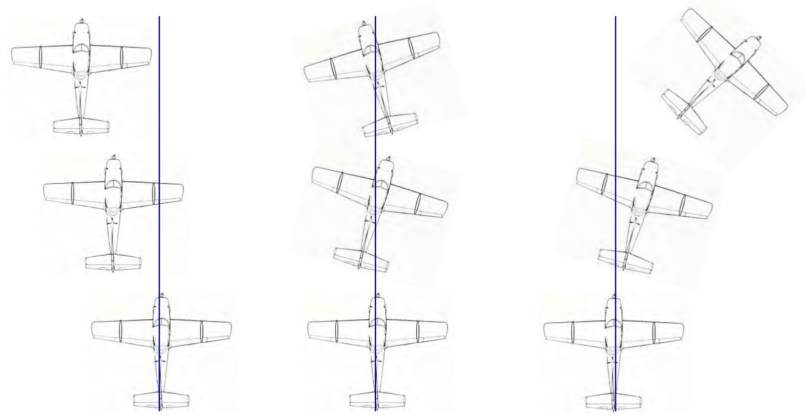
Control-Configured-Vehicle Modes with VRA Side Force

Side Step | **Yaw Pointing** | **Flat (Skid) Turn**



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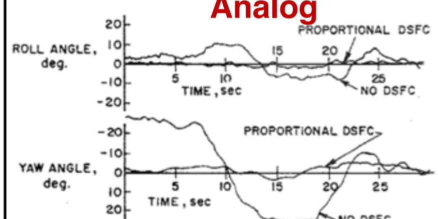
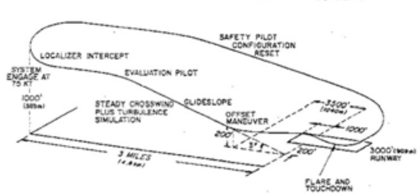
Evaluation of Direct-Side-Force Control Modes with VRA

Analog





Digital

Table 1 Controller-command pairings

Controller	$\Delta\delta P$	$\Delta\delta T$	$\Delta\delta S$
Mode no.	Command		
1,2	Δr	$\Delta\beta$	Δp
3	$\Delta\beta$	Δr	Δp
4	$\Delta\beta$	Δp	Δr
6,7,8	Δr	$\Delta\beta$	$\Delta\phi$[a]

[a] Plus secondary Δr command

CHR vs Mode #

Table 3 Pilot ratings of the landing approach task

Mode no.	TF	FA	MC
2	4.75	3.5	3.25
3	5.0	4.75	5.75
4	6.5	7.5	7.75
6[a]	3.2	3.5	3.0
7	5.0	3.75	3.5
8	3.5	3.75	4.0

[a] 3 runs, engineering pilot

Binnie, Stengel, JGC, 1979 *Grunwald, Stengel, JGCD, 1985*

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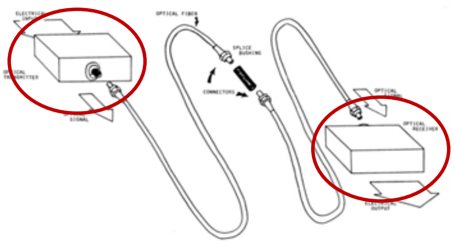
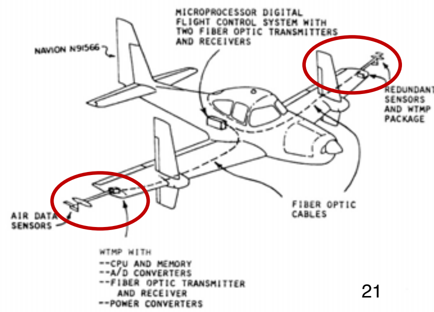
Digital Fiber-Optic Air-Data Signaling

- Angle-of-Attack and Sideslip Angle Sensors
- Z80 Wingtip Processors
  - STD card cages, 3 boards
  - Siecor 155 multimode fiber
- Optelecom 2100 transceivers





Farry, Stengel, IEEE TAES, 1983

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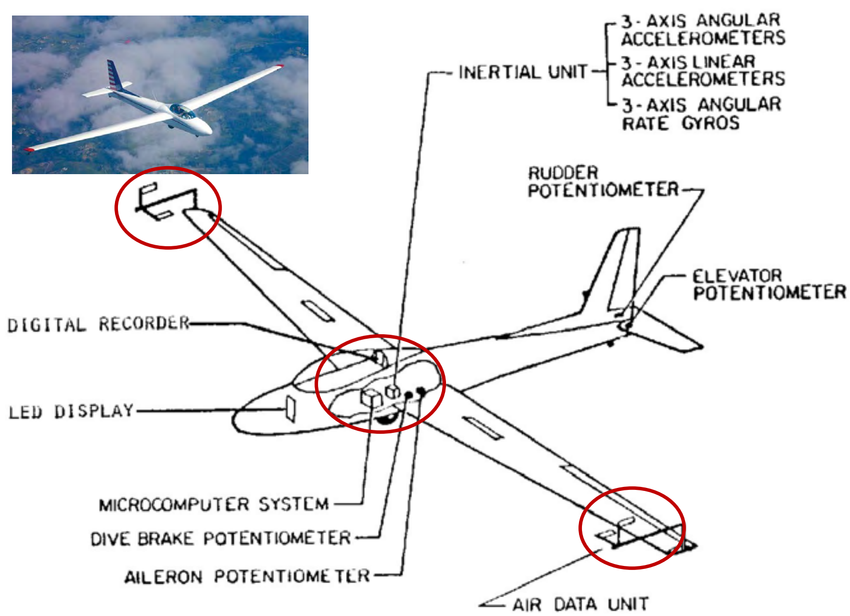
Schweizer 2-32 Sailplane



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System Identification Using Estimation Before Modeling

- State estimate using <u>optimal smoother</u>
- Multivariate regression to <u>model</u> aerodynamic coefficients

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Sri Jayantha, Stengel, JA, 1988

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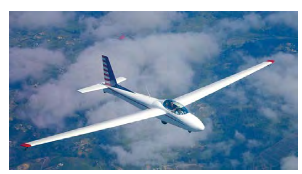
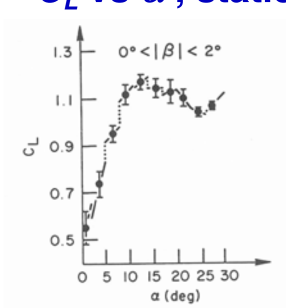
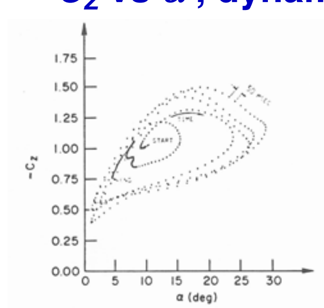
6-DOF Nonlinear High-Alpha Parameter Identification



C_L vs α, static



C_Z vs α, dynamic



Post-stall C_L

Apparent Hysteresis

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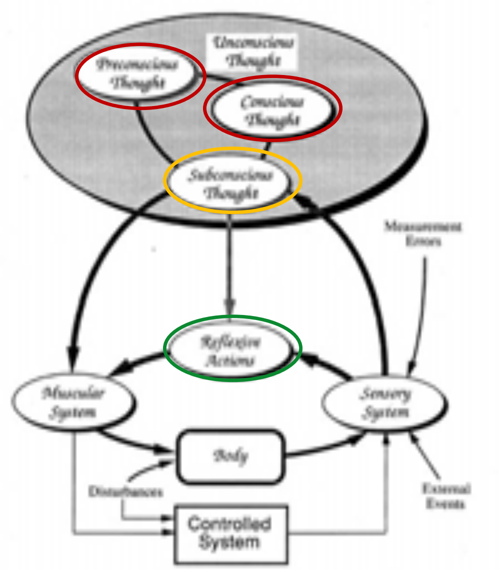
Toward Intelligent Control Systems

Hierarchy of Declarative, Procedural, and Reflexive Actions

- Conscious Thought
- Unconscious Thought
  - Subconscious Thought
  - Preconscious Thought
- Learned Behavior
- Reflexive Behavior



Stengel, IEEE CSM, 1991, IEEE TSMC, 1993

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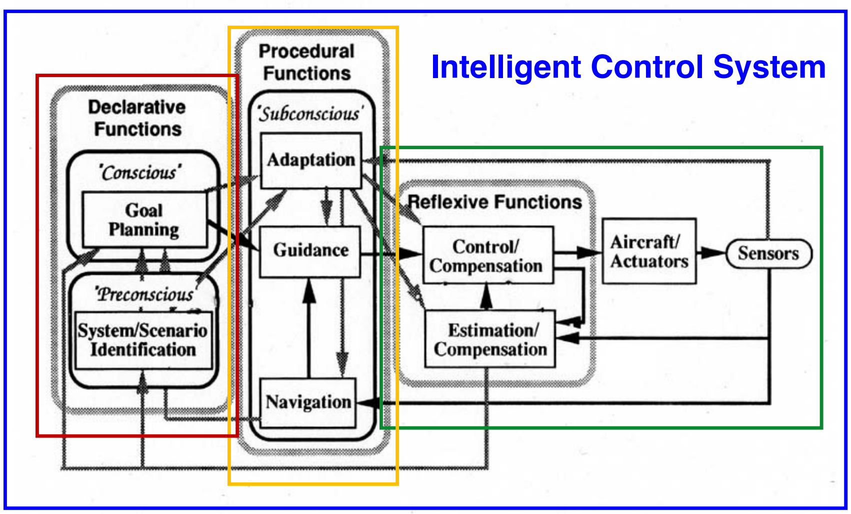
Elements of Intelligent Control



Declarative Functions		*Expert Systems, Decision Trees*
Procedural Functions	*modeled by*	*Estimation and Control "Circuits"*
Reflexive Functions		*Control Laws, Neural Networks*

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Stochastic Robustness

http://www.stengel.mycpanel.princeton.edu/RayTAC1991.pdf
http://www.stengel.mycpanel.princeton.edu/Robustness.pdf

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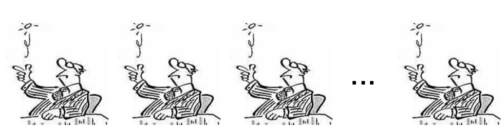
Estimating the Probability of Coin Flips

- **Single unbiased coin**
  - **Exhaustive search: Correct answer in 2 trials**
  - **Random search (20,000 trials)**
- **21 coins**
  - **Exhaustive search: Correct answer in = 2^{21} = 2,097,152 trials**
  - **Random search (20,000 trials)**



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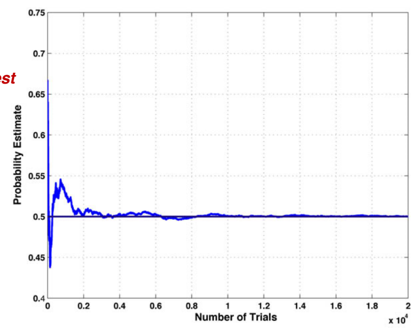
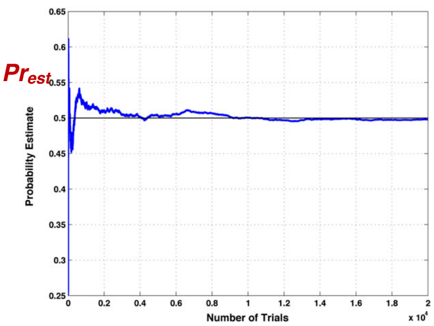
Coin Flip, Monte Carlo Results Essentially the Same (20,000 Trials)

- Single coin
- 21 coins





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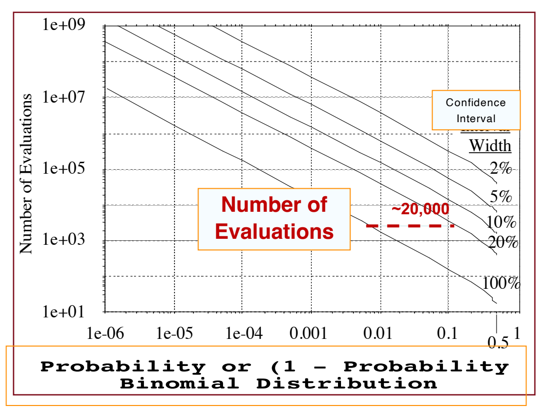
Design Outcomes Follow Binomial Distributions

- OUTCOME has BINOMIAL DISTRIBUTION: Satisfactory/Unsatisfactory
- Confidence intervals
  - Actual probability
  - ~ Number of trials
- INDEPENDENT of
  - # of uncertain parameters
  - Parameter probability distributions



Ray, Stengel, IEEE TAC, 1991

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Probability of Stable Control of an Unstable Plant

Nominal eigenvalues

$$\lambda_{1-4} = -0.1 \pm 0.057j, \quad -5.15, \quad 3.35$$

Air density and airspeed: Uniform distributions (±30%)

Ten aero coefficients: Gaussian distributions (σ = ±30%)

$$\mathbf{p} = \begin{bmatrix} \rho & V & f_{11} & f_{12} & f_{13} & f_{22} & f_{32} & f_{33} & g_{11} & g_{12} & g_{31} & g_{32} \end{bmatrix}^T$$

Environment | **Open-loop Dynamics** | **Control Effect**

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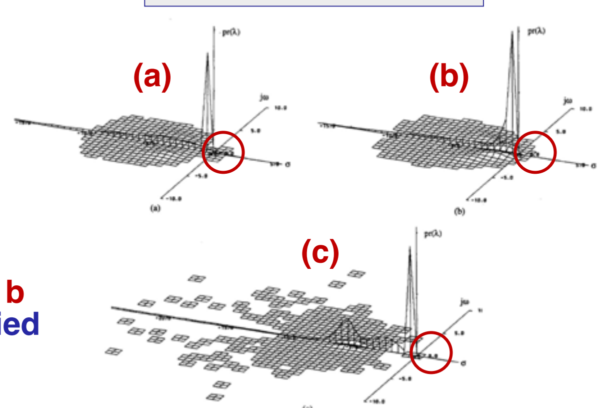
Fixed-gain, 2-input LQ Regulators

- Case a) LQR, LOW control weighting
- Case b) LQR, HIGH control weighting
- Case c) Case b gains multiplied by 5 for BANDWIDTH RECOVERY

Stochastic Root Locus



25,000 trials

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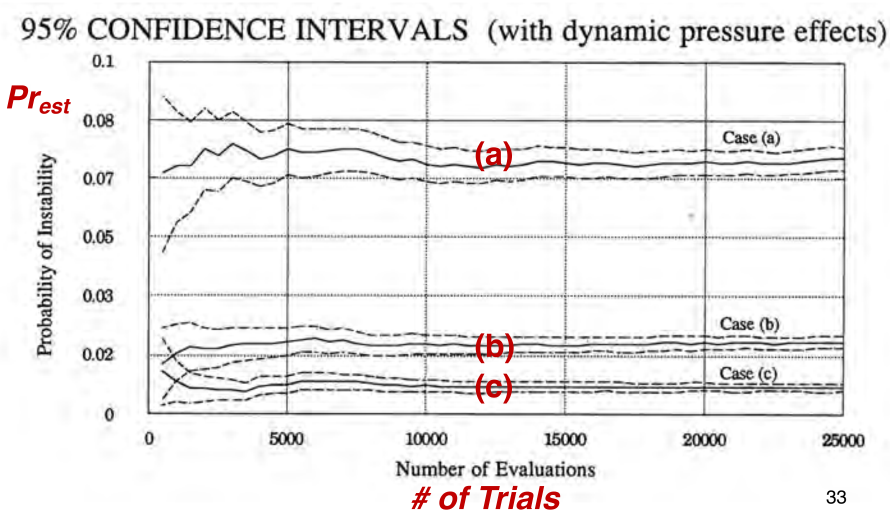
Probabilities of Instability for Three Cases, 25,000 trials



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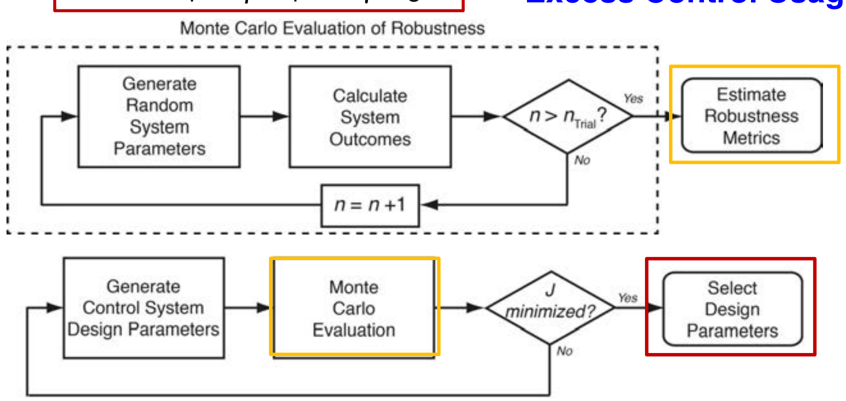
Monte Carlo Design

- **Weighted quadratic design cost, *J*:**

$$J = \alpha Pr_I^2 + \beta Pr_P^2 + \gamma Pr_C^2$$

- **Instability**
- **Poor Performance**
- **Excess Control Usage**



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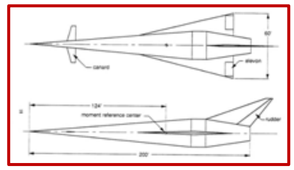
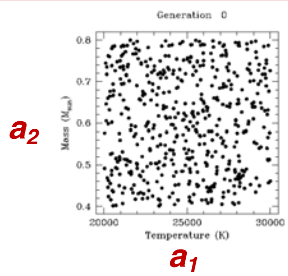
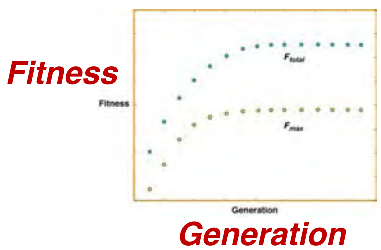
Robust LQ Control of a Hypersonic Aircraft



- **Nonlinear longitudinal model,** ***Shaughnessy et al, 1990***
  - ***Operating Point: Mach = 15, h = 110,000 ft***
- **28 uncertain parameters, 20,000 trials**
- **Cost Indices: Stability + 38 step-response metrics**
- **Design parameters: Q and R diagonal elements**
- **GENETIC ALGORITHM search for optimal LQ weights**





Marrison, Stengel, JGCD, 1998

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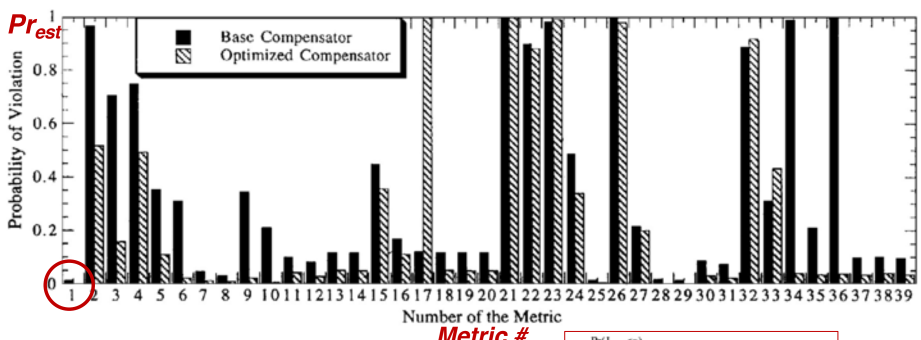
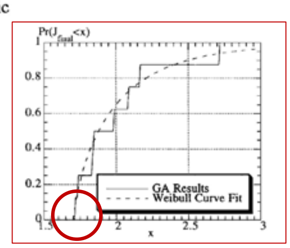
Robust Fixed-gain LQ Control of a Hypersonic Aircraft



- **Multiple trials**
- **WEIBULL DISTRIBUTION estimates minimum cost**



Marrison, Stengel, JGCD, 1998

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Nonlinear Dynamic Inversion

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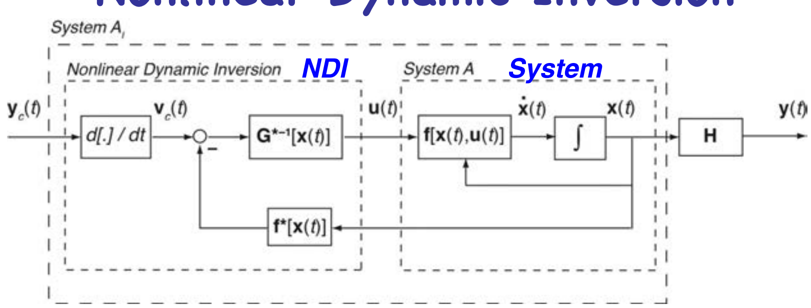
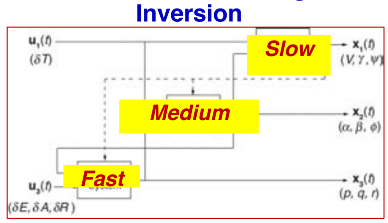
Nonlinear Dynamic Inversion



Time-Scale Partitioning of Inversion



Lane, Stengel, Automatica,1988
(after Singh, Rugh, 1972)

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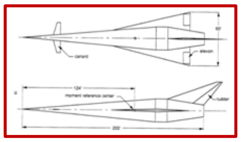
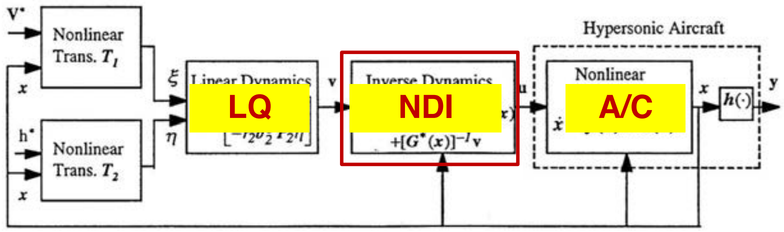
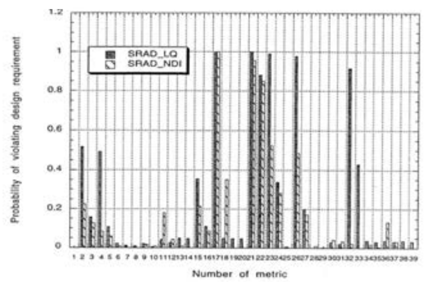


Robust Fixed-gain LQ/NDI Hypersonic Control



- **Genetic Algorithm plus NDI, 20,000 trials**
- **40% improvement over LQ alone**



Wang, Stengel, IEEE TCST, 2005

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Air Traffic Management Using Principled Negotiation

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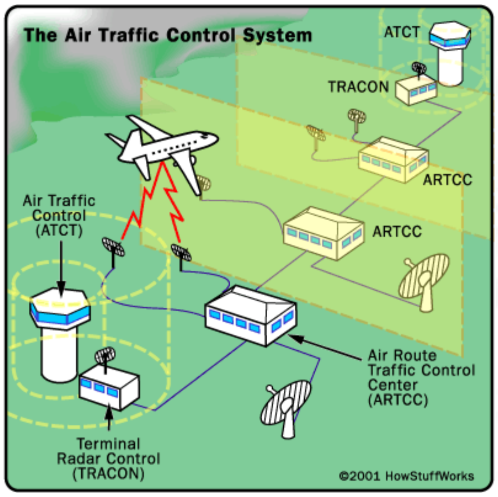
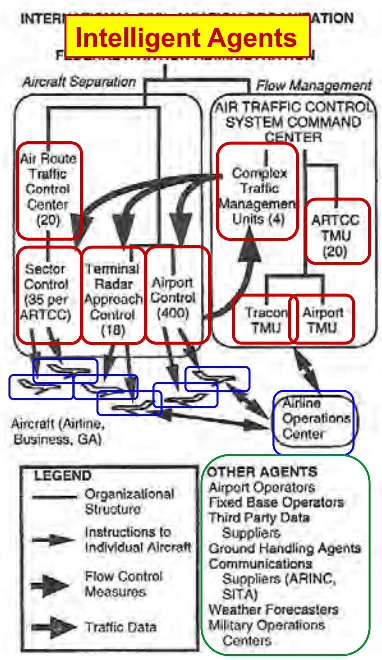
Intelligent Agents in Air Traffic Management





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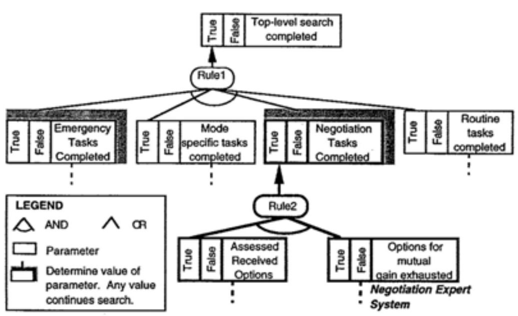
Rule-Based Air Traffic Management

- Top-Down Search of Rule Base



- Optimizing and Satisficing goals

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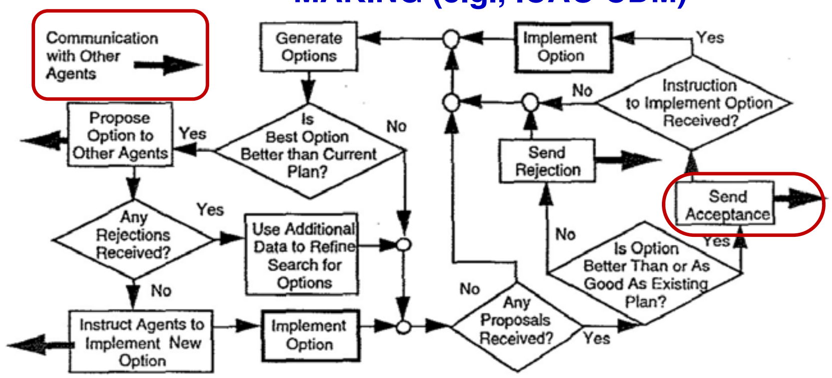
Principled Negotiation* Network

- A networked approach to COLLABORATIVE DECISION MAKING (e.g., ICAO CDM)



Wangermann, Stengel, JGCD, 1999

- Fisher, Ury, *1981*
- *ICAO CDM, 2019*

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Adaptive Neural Networks

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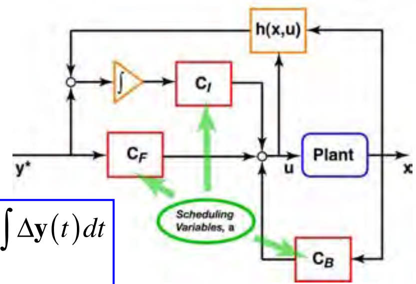
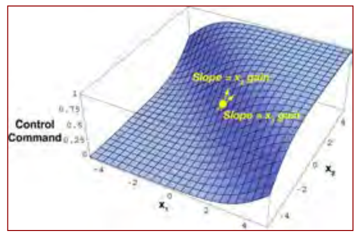
Adaptation by Gain Scheduling

- Proportional-integral controller
- Gains scheduled by **a**



$$\mathbf{u}(t) = C_F(\mathbf{a})\mathbf{y}^* + C_B(\mathbf{a})\Delta\mathbf{x} + C_I(\mathbf{a})\int \Delta\mathbf{y}(t)dt$$
$$\approx \mathbf{c}\left[\mathbf{x}(t), \mathbf{a}, \mathbf{y}^*(t)\right]$$

Linear control gains are gradients of the nonlinear control hyper-surface



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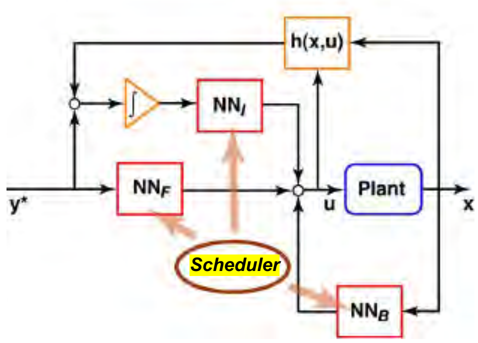
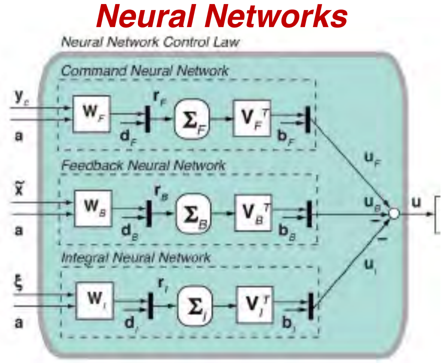
Classical/Neural Synthesis of an Adaptive Control System



Neural Networks



- Shallow, feed-forward networks
- Smooth interpolation of scheduled gains

Ferrari, Stengel, JGCD, 2002

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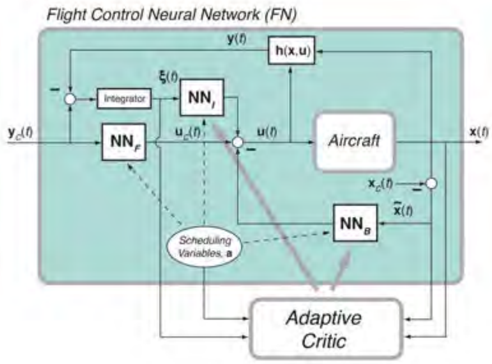
Adaptive Critic Controller
[Dual Heuristic Dynamic Programming]



- **Action Network: Control network weights adapt to improve performance**
- **Critic Network: Cost model adapts to improve evaluation**

Ferrari, Stengel, JGCD, 2004

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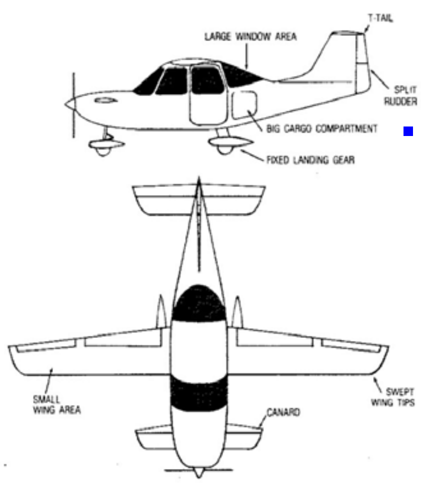
Time to Reinvent the General Aviation Aircraft, 1987



- *Modern-Equipment General Aviation (MEGA-) Plane , 1987*
  - *Triply redundant DFBW*
  - *RNAV, TCAS, IFR*
  - *3-surface control*
  - *Redundant control surfaces*
  - *Simple mechanical devices*
  - *Fixed gear*
  - *Conventional engine*
  - *Automobile-volume pricing*

Stengel, Aerospace America, 1987

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What's Next?

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General Aviation, 2023

2023 Cirrus SR22

2023 Cessna 172

- *MEGA-Plane Proposal, 1987*
  - *Triply redundant DFBW*
  - *RNAV, IFR*
  - *3-surface control*
  - *Redundant control surfaces*
  - *Simple mechanical devices*
  - *Fixed gear*
- ***2023 GA***
- ***$$$$ - New personal aircraft***
- ***Optional FMS-Autopilot (e.g., Garmin "Smart Glide"), Glass cockpit***
- ***Average age of US fleet : 48 years***
- ***Liability insurance***
- ***Kit planes and retrofits***

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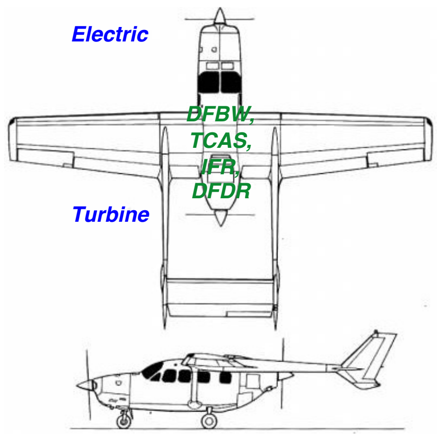
The 2023 MEGA-Plane: Hybrid/Electric



- *Autonomous Operation, DFBW*
  - *Xwing Super Pilot*
  - *Reliable Robotics*
  - *Merlin Labs, Ribbit*

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Contemporary Small Computers: Arduino, Raspberry Pi, & iPhone 15

- c: 2010
- 1 CPU
- 16 MHz clock
- 256 KB, 8-bits
- Single task

- c: 2019
- 4-core CPU
- 1.5 GHz clock
- 8 GB, 32 bits
- Multitask

- c: 2022/3
- 6-core CPU, 5-core GPU, 16-core ANE
- 3.78 GHz clock
- 512 GB, 64 bits
- Multitask

Number of units that weigh 70 lb (AGC weight):

858 *690* *185*

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Advanced/Urban Air Mobility Aircraft

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https://en.wikipedia.org/wiki/List_of_electric_aircraft

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Urban Air Mobility is a Disruptive Technology

- NASA/USAF: AAM National Campaign, numerous contractors, flight testing at Edwards/Armstrong
- FAA: Parts 21, 23; UAM ConOps 2.0 (2023), Innovate28 1.0 (2023)
- Risk Exposure: CREW, PASSENGERS + GROUND-LEVEL FOLKS
- AUTONOMOUS VEHICLES in 3-D
- and ... WHERE/WHO IS THE PILOT?

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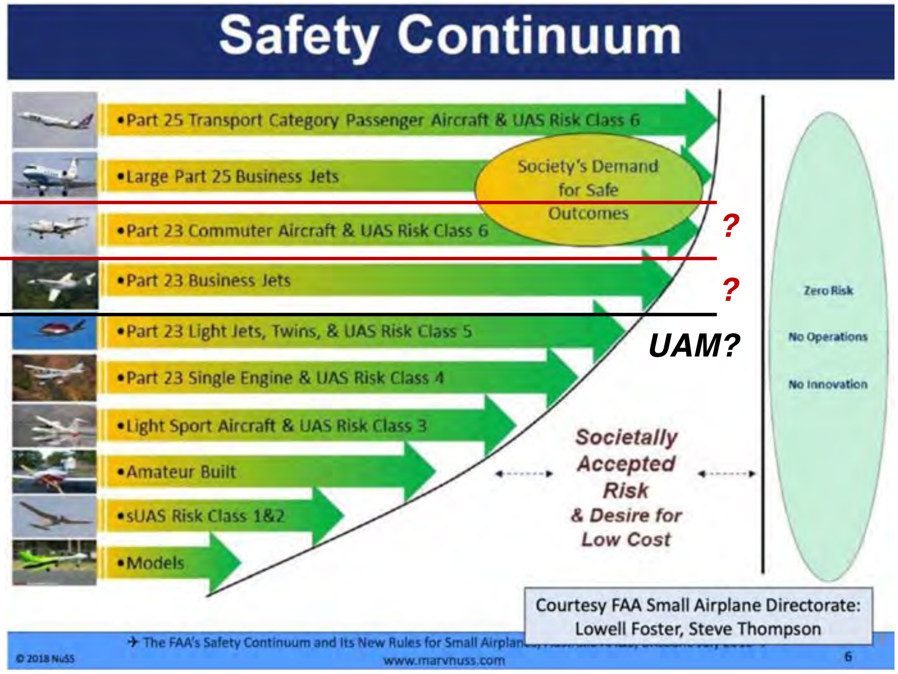

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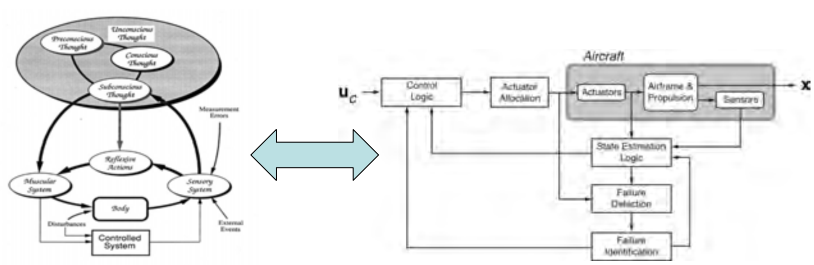
Control System Design and Computer Simulation

"Large-Language" AI Crew Model | **"Large-Language" AI Aircraft Model**



Handelman, Stengel, AIAA, 1989
Gopisetty, Schramm, Stengel, AIAA ASM, GNC, ACC, 1998

- **Real-time scenarios**
  - **Pre-flight checklist**
  - **In-flight-failure/out-of-envelope response list**
- **Stochastic evaluation** (means and variances of all parameters)

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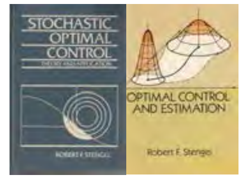
Takeaways



- Goal: Ultra-Reliable DFBW Flight Control
- Stochastic Robustness
- Nonlinear Dynamic Inversion
- Adaptive Critic
- Principled Negotiation
- Large-Language Pilot Models & Flight Simulation = Single Design Approach
- Convert Kit Planes to MEGA-Planes?

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Perspectives on Computation and Flight Control

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- Students
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- ARO
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- NADC
- STI/USAF
- ONERA
- George Schultz Foundation
- Sanders/BAE Systems
- C.S. Draper Laboratory
- TASC
- Princeton University
- AIAA/IEEE

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