SIMULATION FUNDAMENTALS

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OUTLINE

- Introduction
  - Simulation vs Virtual Reality
- Brief History of Flight Simulation
- Human-machine Systems
  - System Dynamics
  - Control Theoretic Approach
  - Human Operator Modeling
  - Requirements Determination
- Simulator Systems Overview
- Problem Areas
- Future Applications

VIRTUAL REALITY

WHAT IS IT?

VIRTUAL REALITY

WHAT IS IT?

Human in the loop
SIMULATION!!!!

Virtual Environment

Definition

Creating a synthetic replica of a real

environment sufficient for the task at hand; e.g. a simulation.

Presence

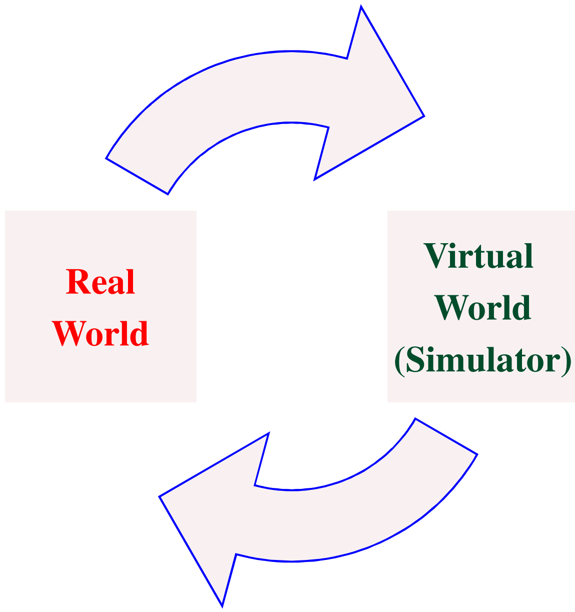
Creating a sense of being present in the virtual environment for control or observation- also telepresence

Augmented reality

Sometimes called mixed reality – just what the words indicate

Constraint - Real-time for control

Simulation Objective



- Take real world attributes
- Map them into the virtual world
- Yield **behavior** in the virtual world which emulates real world behavior for the same task

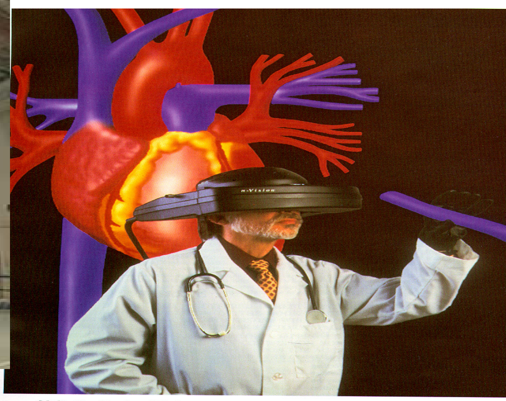
Vehicle Simulation

Concentration

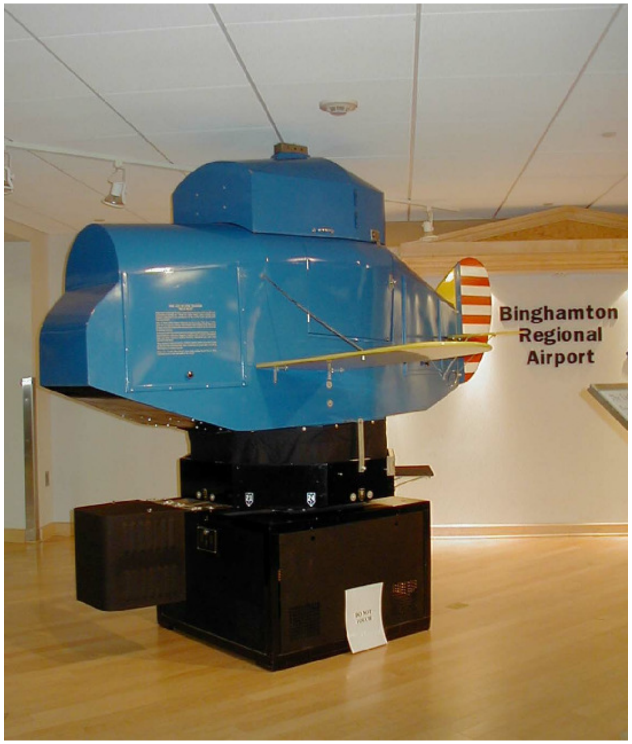
Human - in - the Loop Simulation

Many Different Real World Vehicles

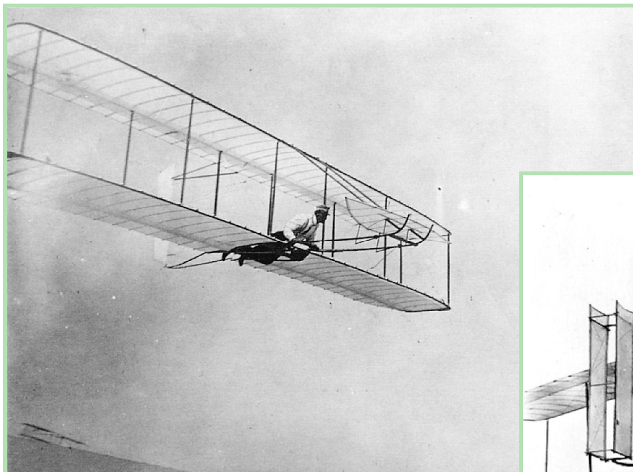
Virtual World Devices (Simulators)



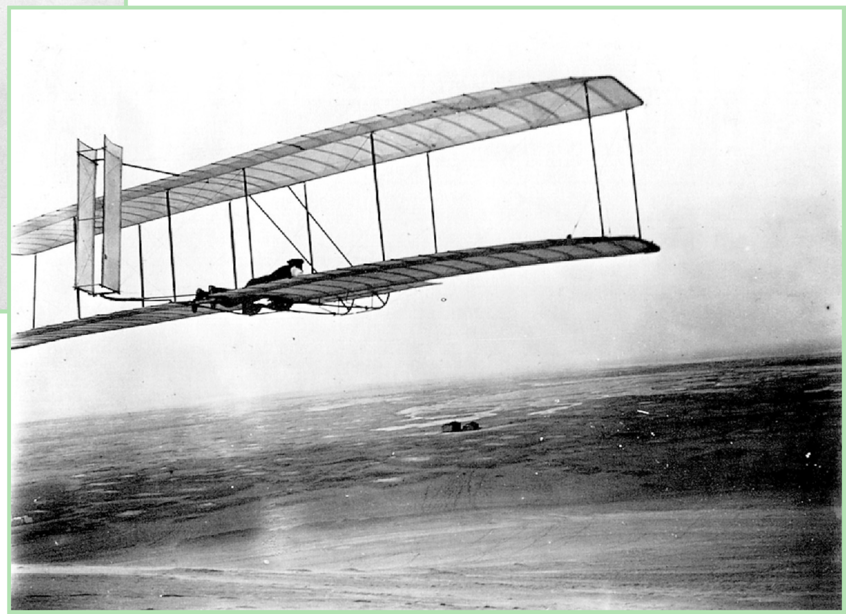
The Pre-Blue Box Years
A Brief History of the Early Days



Wright brothers used gliders to train themselves to fly

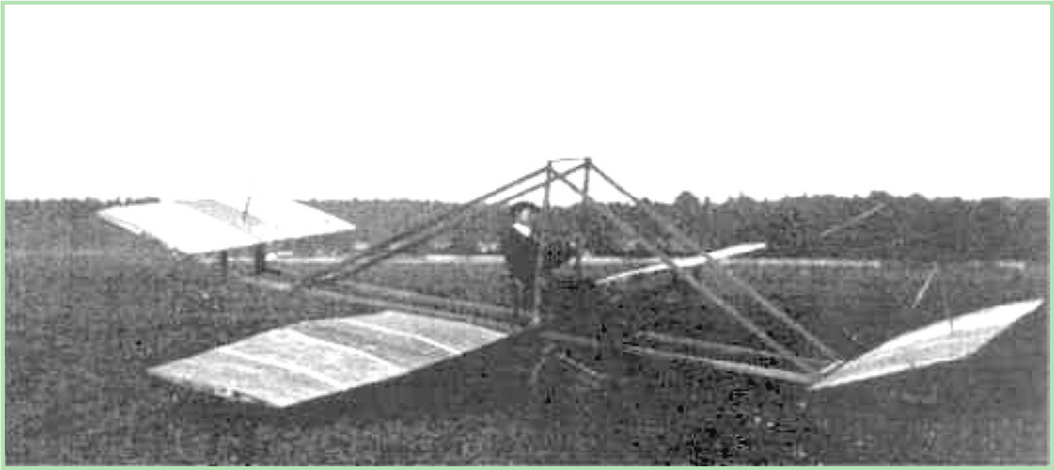


1902 glider

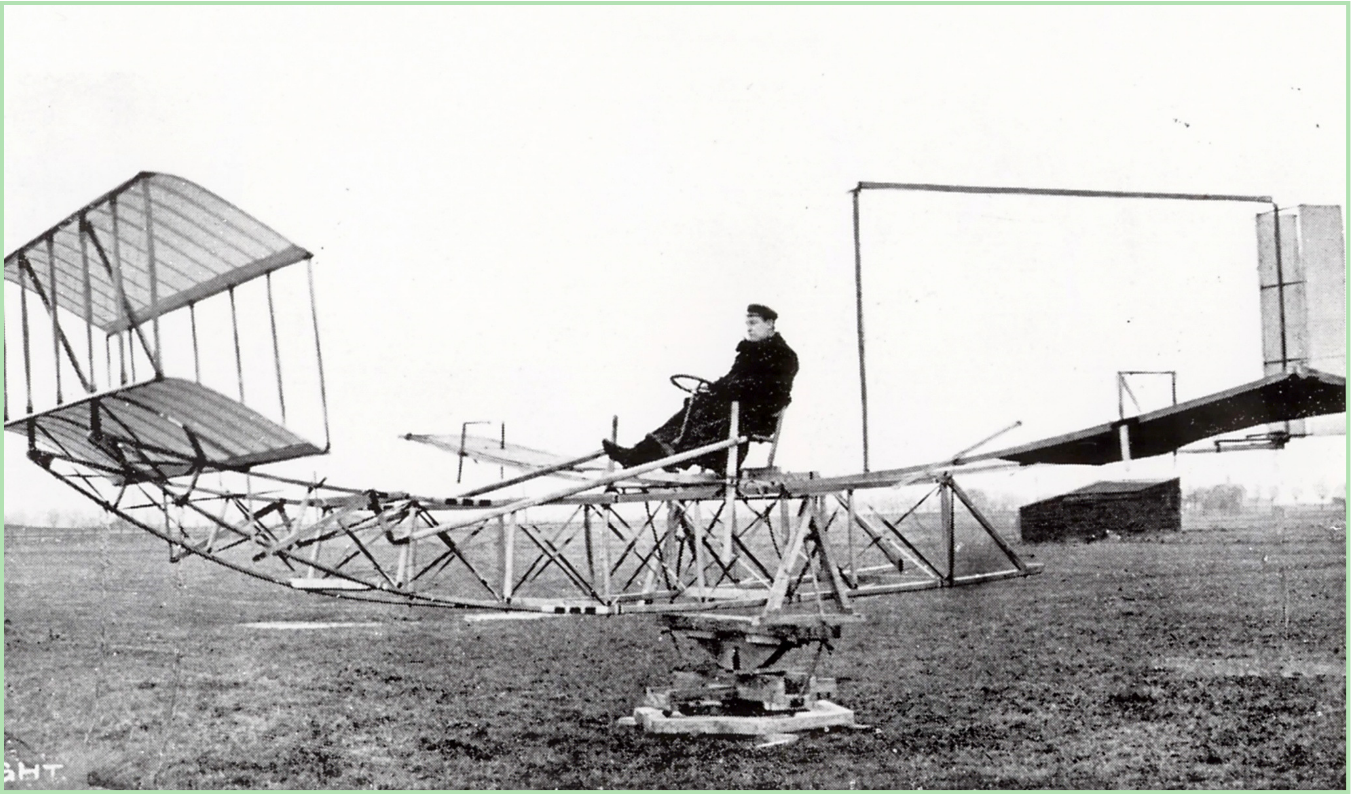


1902 Glider updated with 1903 Flyer rudder

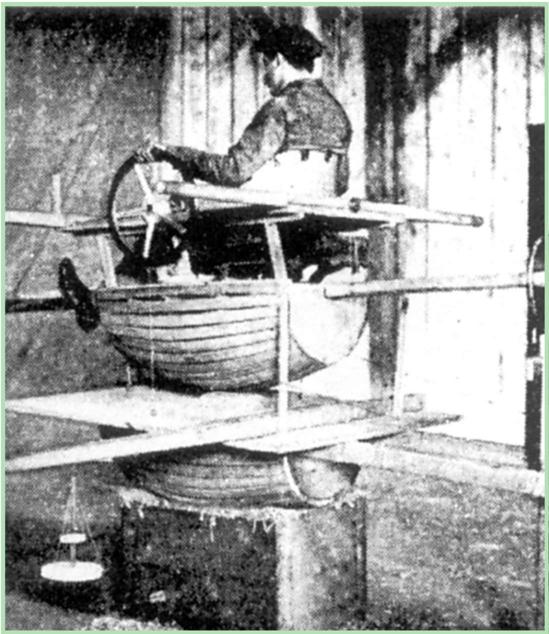
First Trainers Around 1910 Billings Teacher

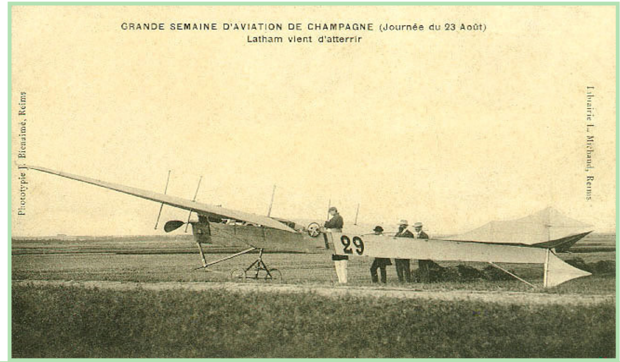


Sanders Trainer ≈ 1910

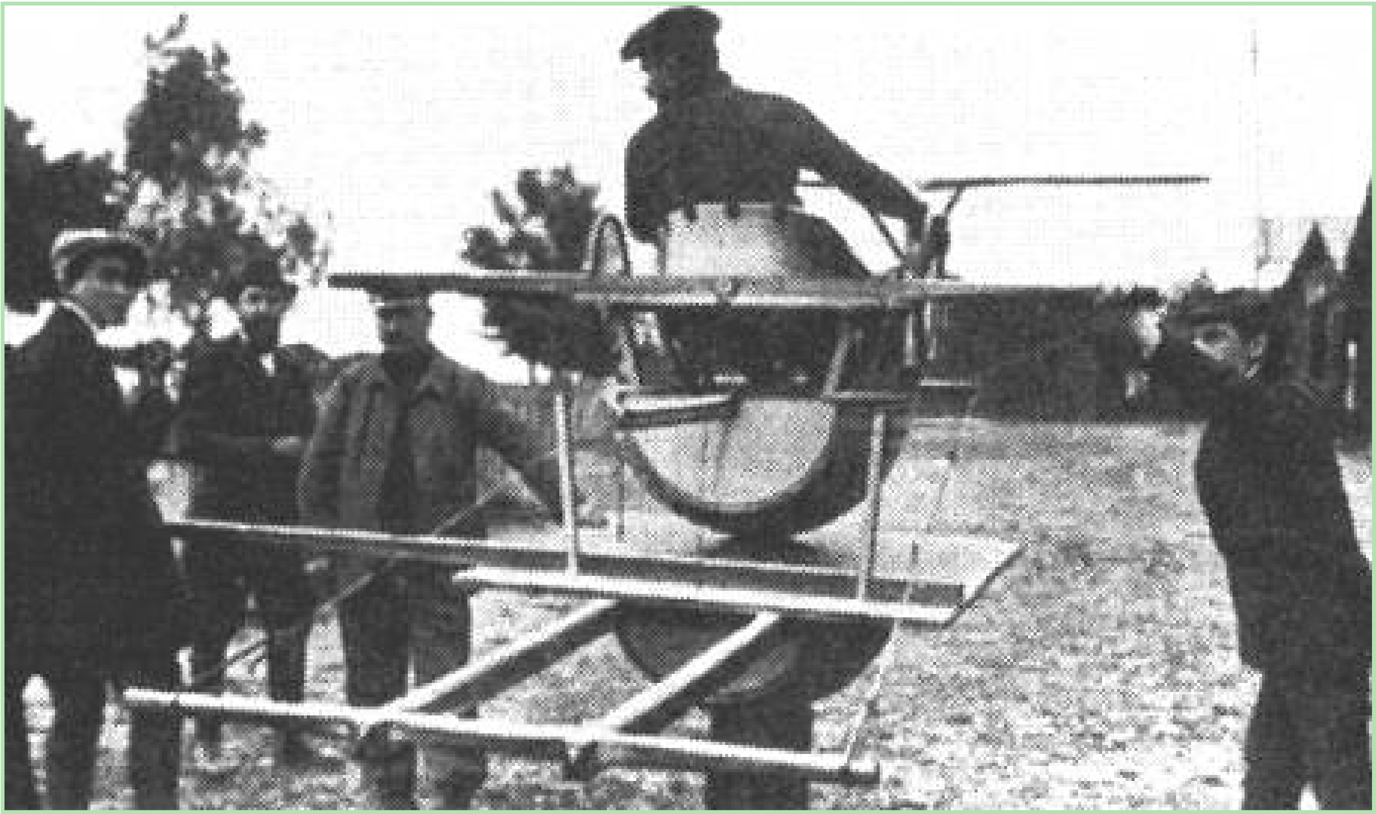


Antoinette aircraft - Side wheel control

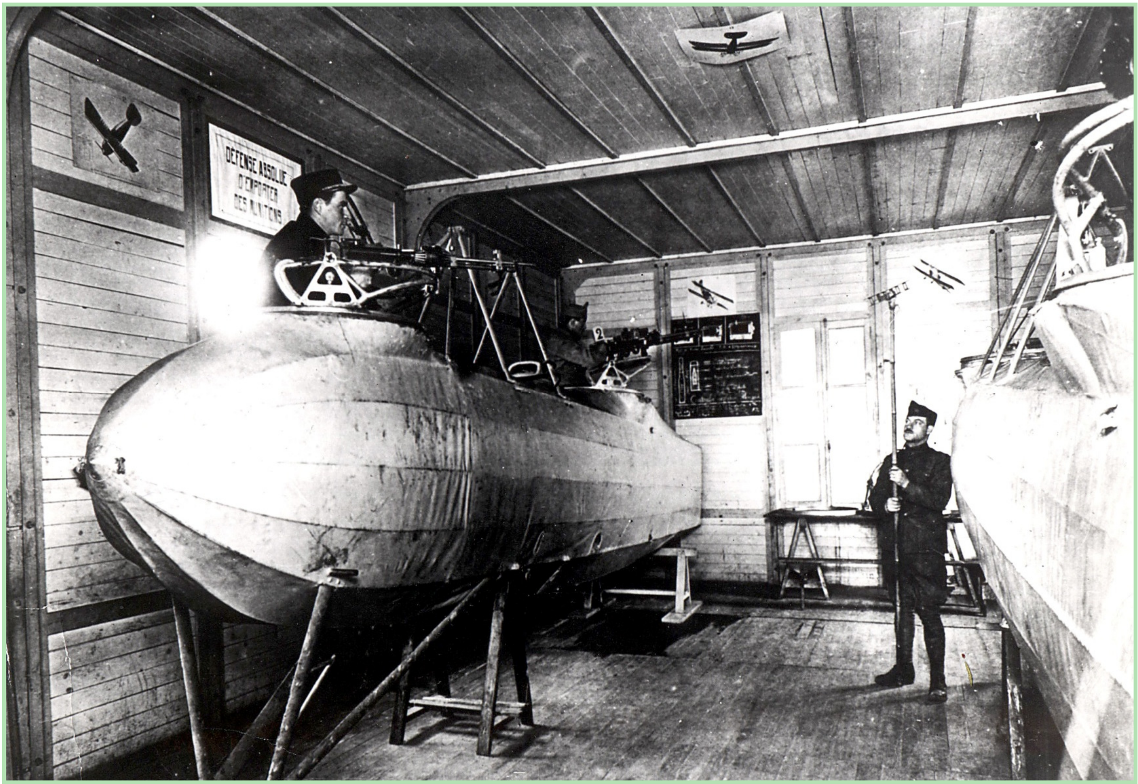




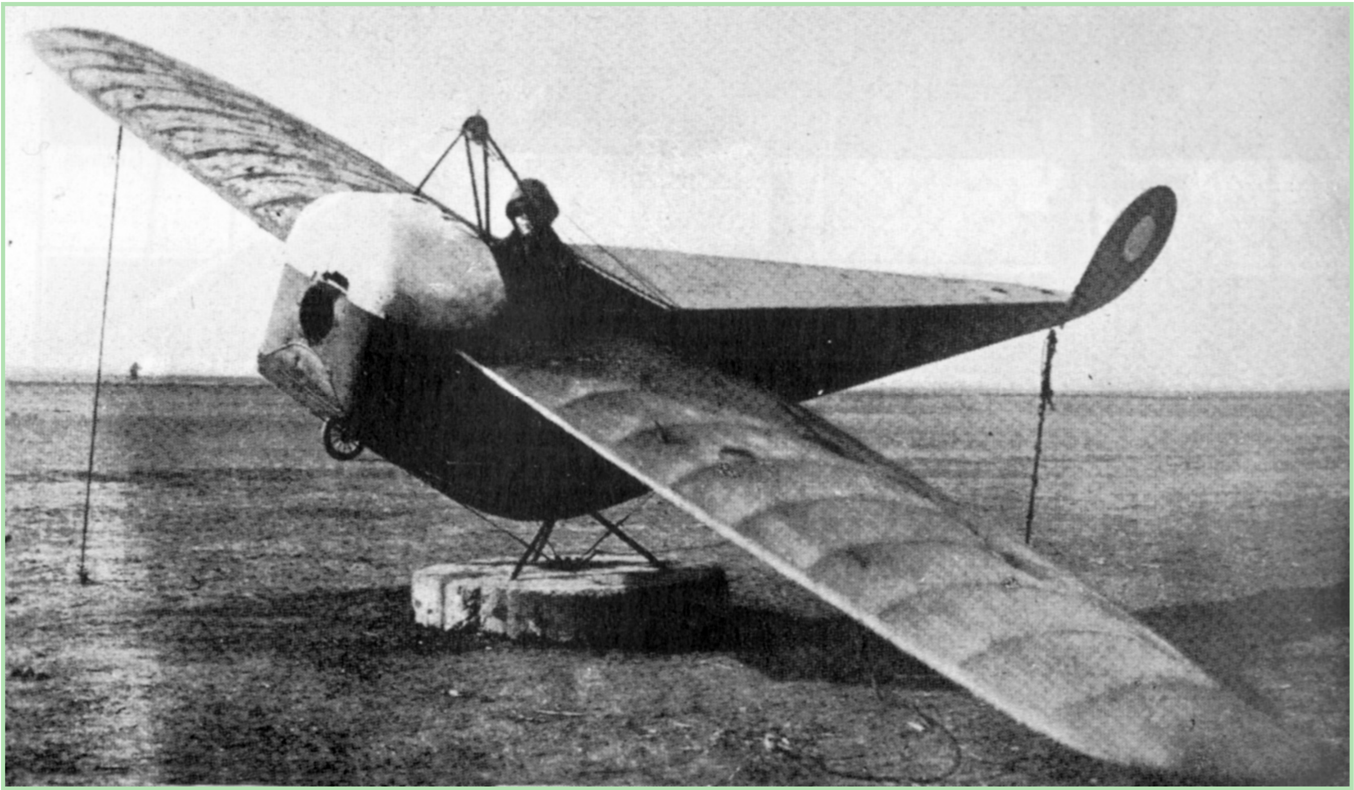
Antoinette Motion Cueing Device
Two barrel halves - External inputs



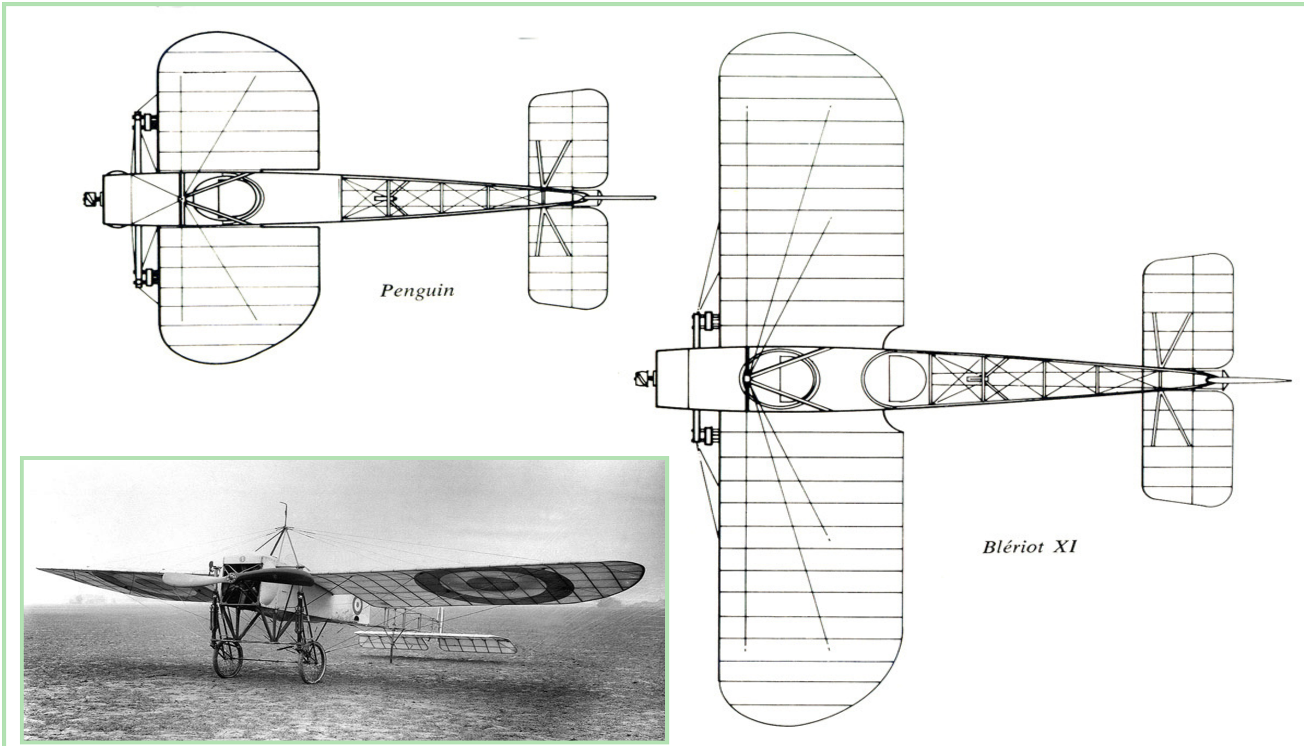
During WWI a number of training devices evolved



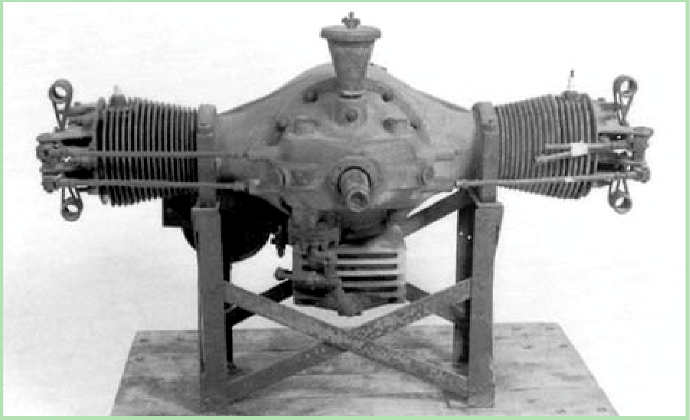
Some wind driven devices continued
Converted Italian obsolete A/C



Penguin "aircraft" more common - Only rolled on the ground



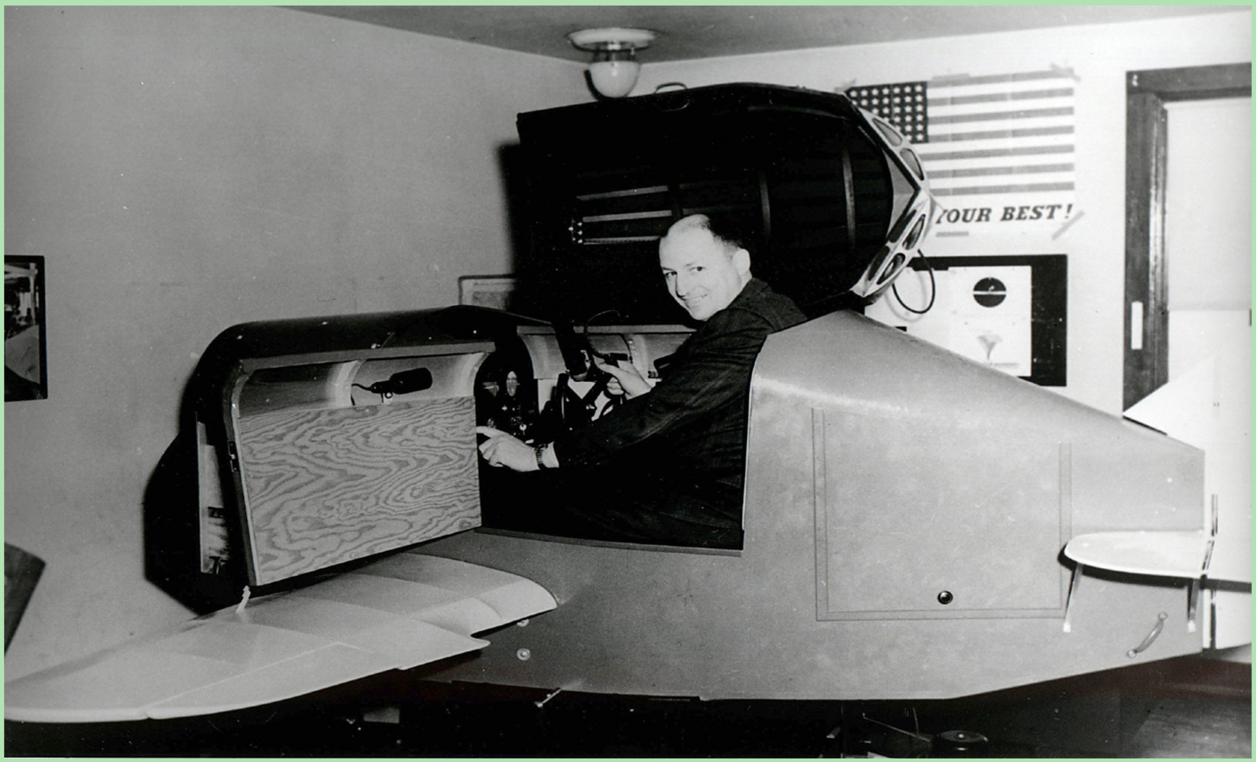
U.S. Air Corp Penguin Aircraft



Breese Penguin
- US Army bought 300, used 5

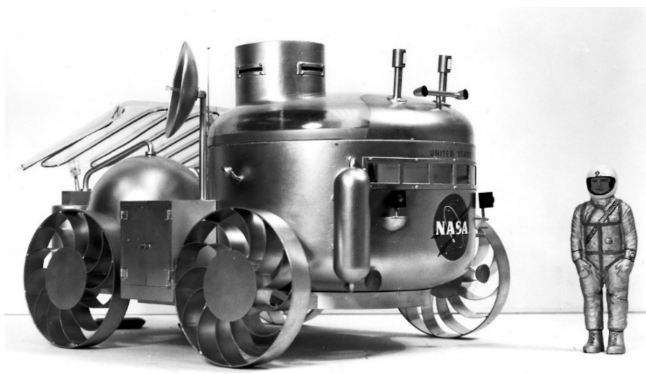
This type of training gave Ed Link the idea for a motion based trainer

Ed Link (1904 - 1981) – Patented the "flight simulator" in 1929

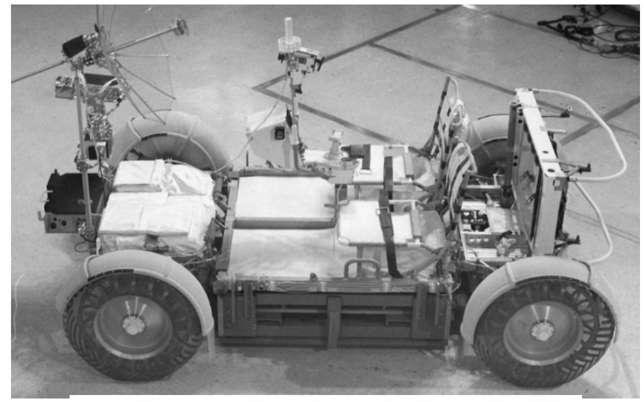


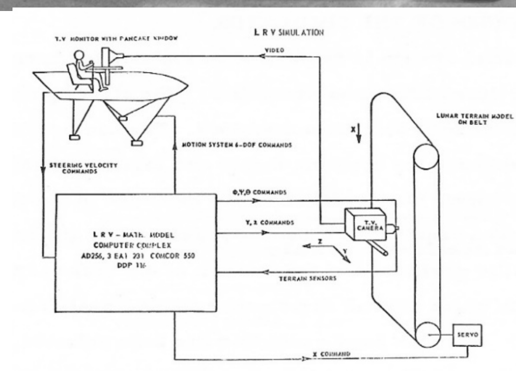
The Inventor of the Flight Simulator

Early NASA Lunar Rover Trainers Concepts



Lunar Roving Vehicle & Simulator w/ SMK23





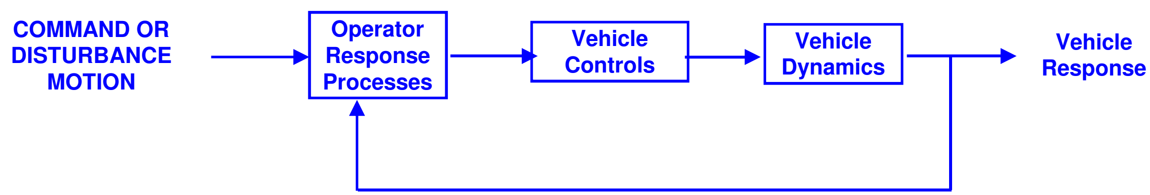
Early Film-based Driver Trainer

Introduction to Man-machine Systems

Modern Approach to Flight Simulation

Employs a control theoretic methodology to man – machine systems analyses

Vehicle Control Is the Control of Vehicle Motion



Operator considered as an element of a control loop.

Human-Machine Systems

Definition:

Dynamic interaction and manual control of dynamic systems.

Includes:

Real and virtual systems

How does the discipline of MMS differ from;

Human Factors?

Ergonomics?

Approach is control theoretic !

Examples of Human-machine Systems

+Own Vehicle
- Ground Vehicles
- Aircraft
- Spacecraft
- Water Borne Vehicles

+Teleoperator Systems
- Telerobotics
- Telemedicine

+Remotely Controlled Vehicles
- Aircraft
- Deep Submergence
- Planetary Surface Explorers

+Simulator Applications
- Training
- Research
- Engineering/Design
- Education
- Entertainment

Note: All systems may contain both real and virtual components

Human Error in A/C Fatal Accidents

In spite of automation crew error record worsened

- **Study 1970 -79**
  - **Crew error 61%**
  - **Maint. & ATC 48%**
  - **Weather 46%**
- **Contributing Factors**

- **Study 1988-1997**
  - Crew error 73%
  - A/C Failure 10%
  - Maintenance 6%
  - Weather 5%
  - ATC 4%
  - Other 2%
- **Attributed factors**

Causes of Fatal Accidents by Decade

(percentage) – Source: planecrashinfo.com

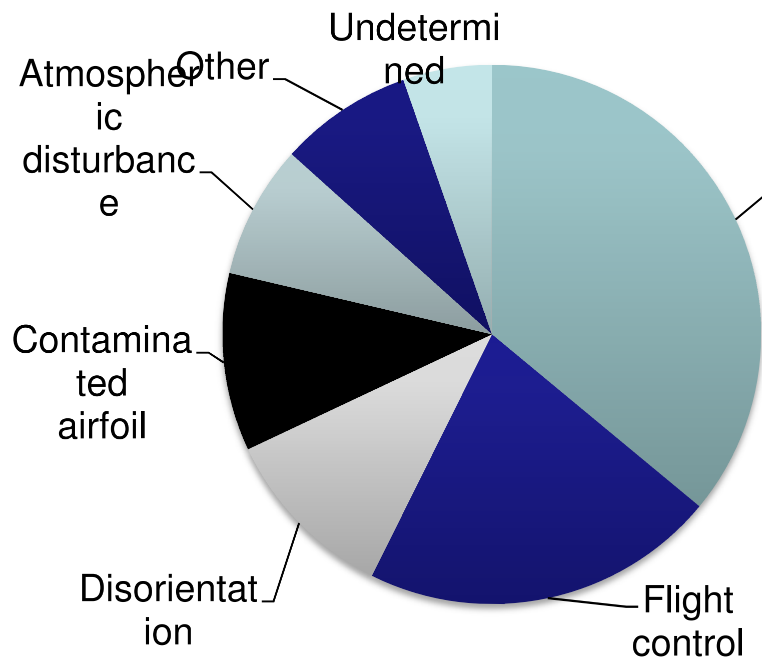
Cause	1950s	1960s	1970s	1980s	1990s	2000s	All
Pilot Error	41	37	29	30	31	30	33
Pilot Error (weather related)	11	17	15	16	19	19	16
Pilot Error (mechanical related)	7	3	4	4	6	3	4
Total Pilot Error	59	57	48	50	56	52	53
Other Human Error	4	7	10	6	7	9	7
Weather	14	11	10	12	9	8	11
Mechanical Failure	20	19	21	21	21	25	21
Sabotage	3	4	9	10	7	6	7
Other Cause	0	2	2	1	1	0	1

Human Factors Analysis of NA Aviation Accidents 1990 - 1998

	Military	Commercial	Gen. Aviation
Skill based	55%	62%	78%
Decision	52	30	36
Perceptual	32	7	5
Violation	29	22	12

Shappell S. and D. Wiegmann, "*HFACS Analysis of Military and Civil Aviation Accidents: A North American Comparison " ISASI 2004*"

Upset and loss of control events in transport airplanes 1993-2007

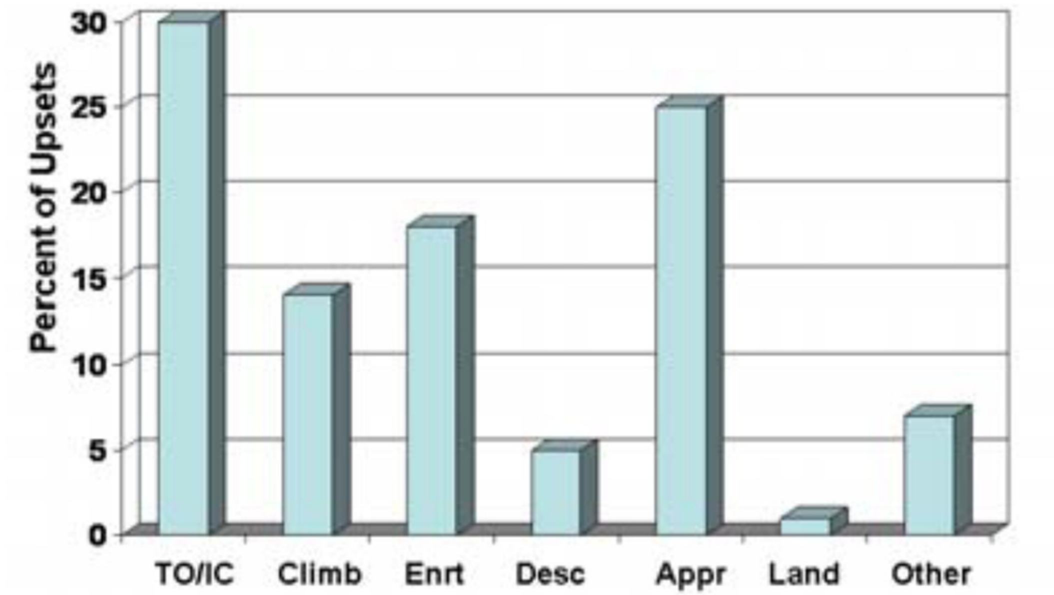


75 events

3261 fatalities

*Lambregts, A.A., et. al., "Airplane Upsets: Old Problem, New Issues, AIAA Paper 2008-6867, AIAA Modeling and Simulation Conference, Honolulu, HI, 2008

Upsets by Phase of Flight



Newman 2012

Why Use Simulators to Train Vehicle Operators?

- Might be the only option
- More efficient
- More effective in many cases
- Safer
- More cost effective
- Availability

Difficult Control Task

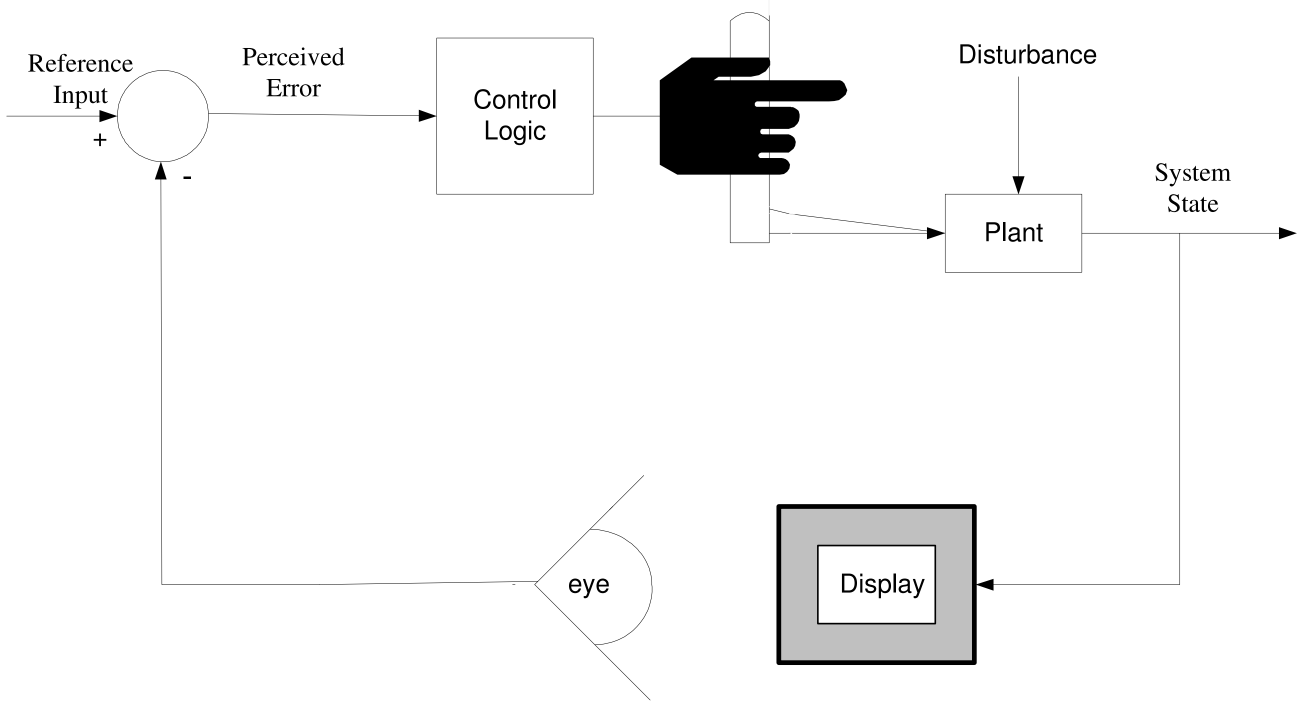
An Important Area of MMS Study

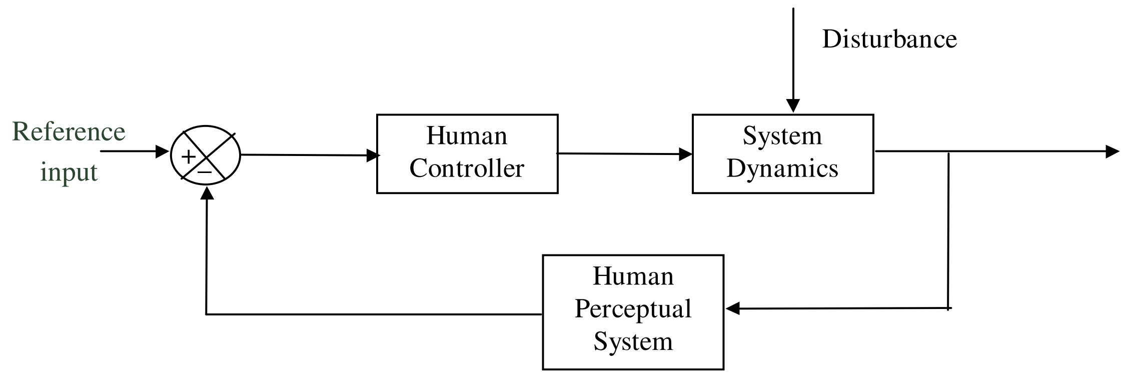
- **How human performance/behavior/learning are affected by system characteristics**
  - Real/Virtual systems (or combinations)
  - System dynamics
  - Level of automation
  - Human operator characteristics
    - Level of experience
    - Physical condition
    - Age
    - Sex
  - Environment (EG motion, visual, sound, Etc.)

Major Disciplines Involved in Analysis and Design

- Dynamic System Modeling
- Human Perception
- Information Systems
- Human Behavior
- Decision Making
- Manual Control
- Hardware Development
- Software Development

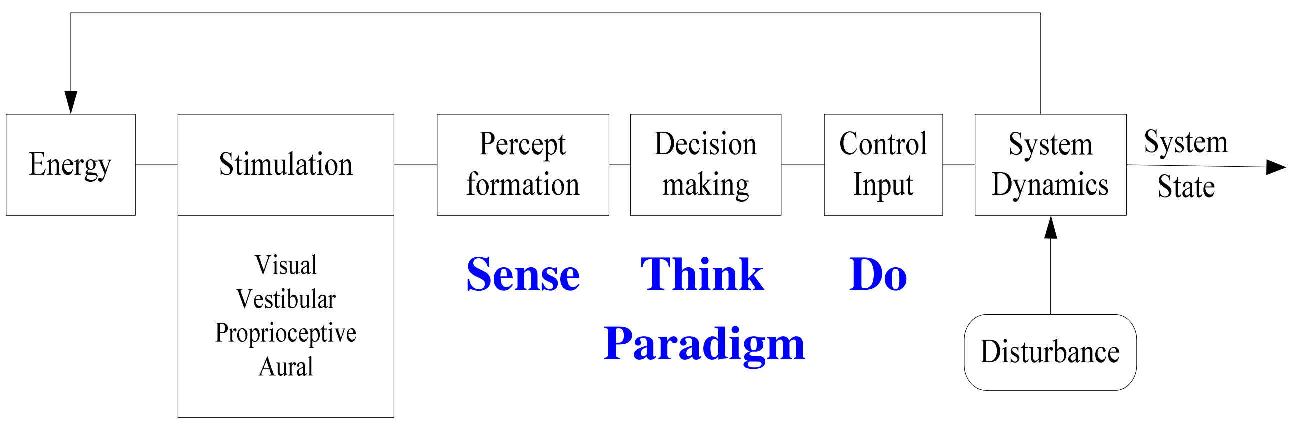
Manual Control System



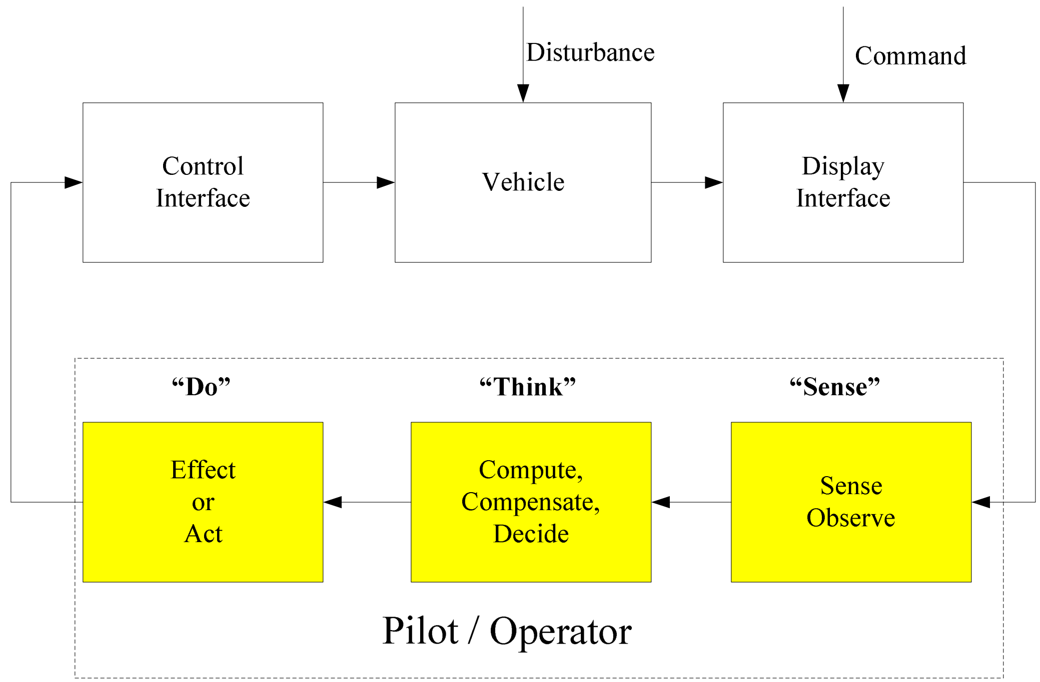


MAN-MACHINE SYSTEM BLOCK DIAGRAM

Closed Loop Human Control Behavior

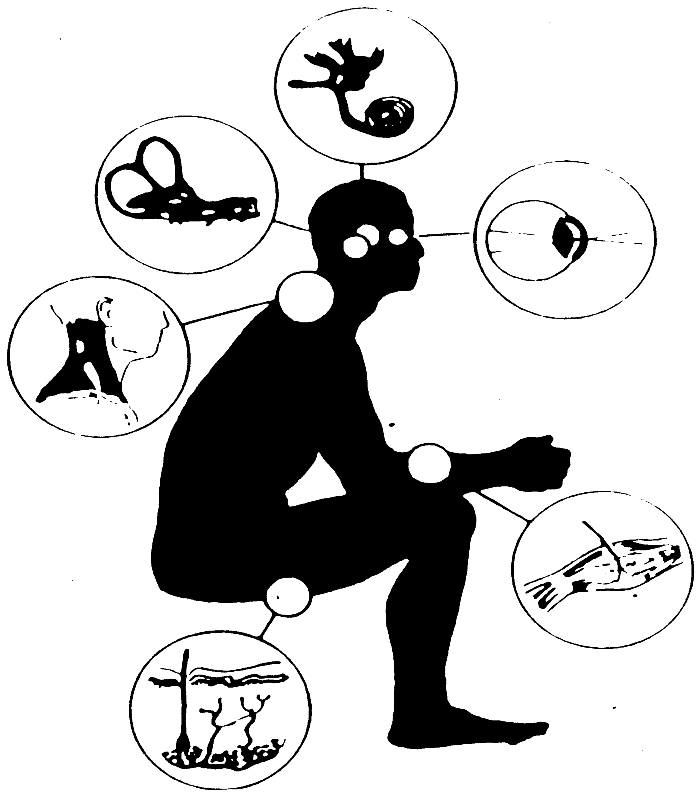


Sense -Think -Do Paradigm



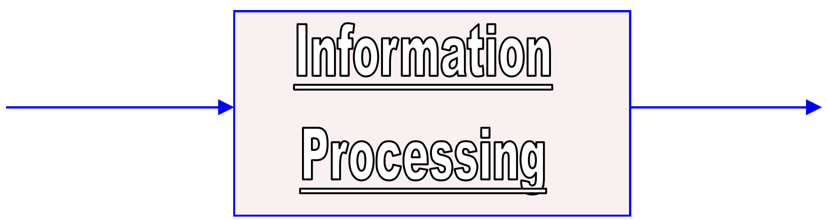
Modified after Baron, S. in Weiner, E.L & Nagel, D.C.
"Human Factors in Aviation". Academic Press, 1988

Human Perception Is an Integrated Process



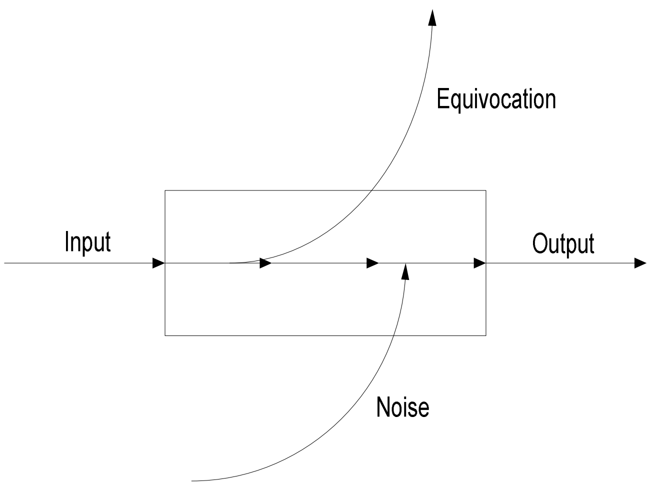
Information

A set of inputs mapped into a set of outputs according to criteria which are independent of the energy transactions involved.



Taxonomy of Information Processing

- **Information Reduction**
  - The input has more complexity than the output.
- **Information Transmission**
  - The input is mapped into the output one-to-one.
- **Information Elaboration**
  - Producing output with more variety than the input.

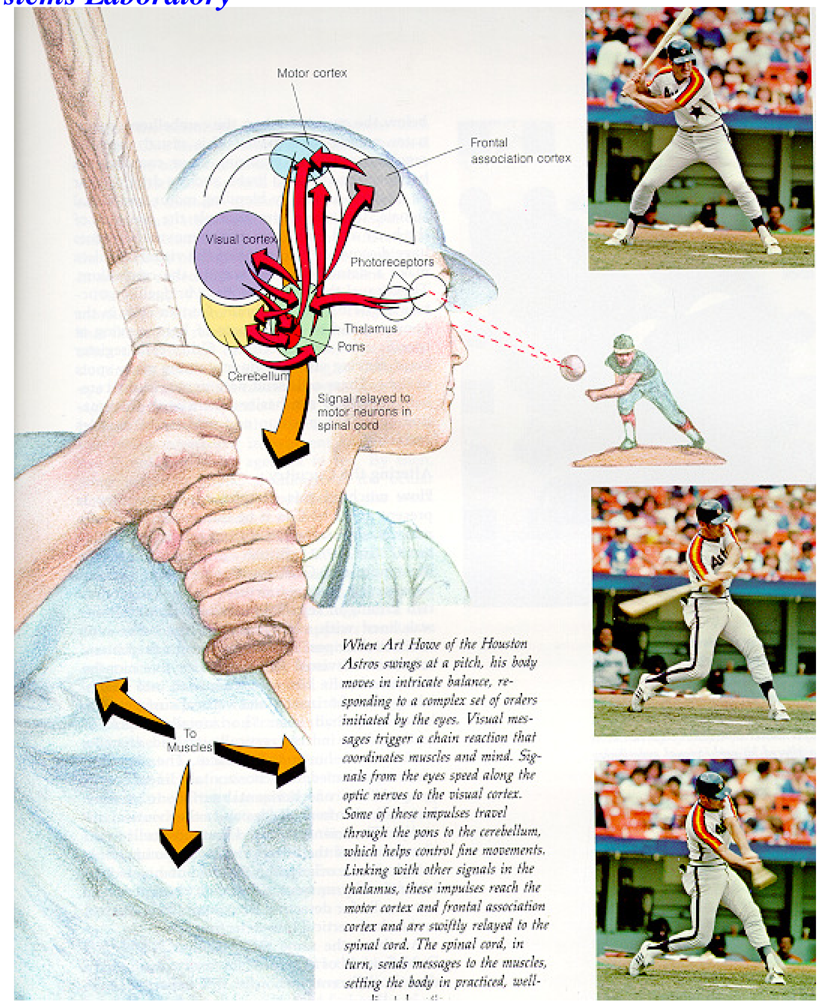


Information Theory

- Information processing is complicated.
- Information theory originated in communication analysis.
  - A means of quantifying communication channels
  - What is sent is not always what is received
  - The output however gives an indication of input
- Information measures quantify the statistical relationship between “evidence” and “ hypothesis”

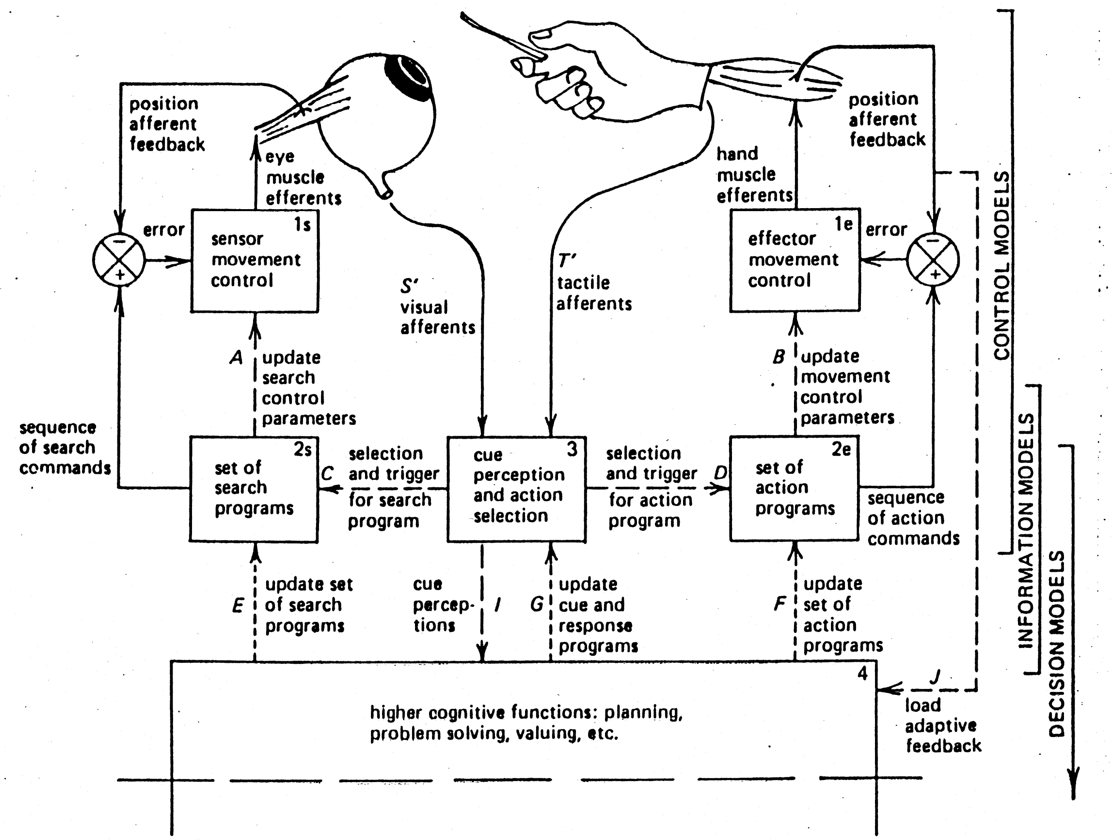
General Characteristics of Decision Making

- Evaluate several sources of information
  - This forms the basis of decision making
- The information is usually probabilistic
  - The information (or cues) are often unreliable, e.g. weather forecast, vibration, Etc.
- The elements of cost and value underlie most decisions.

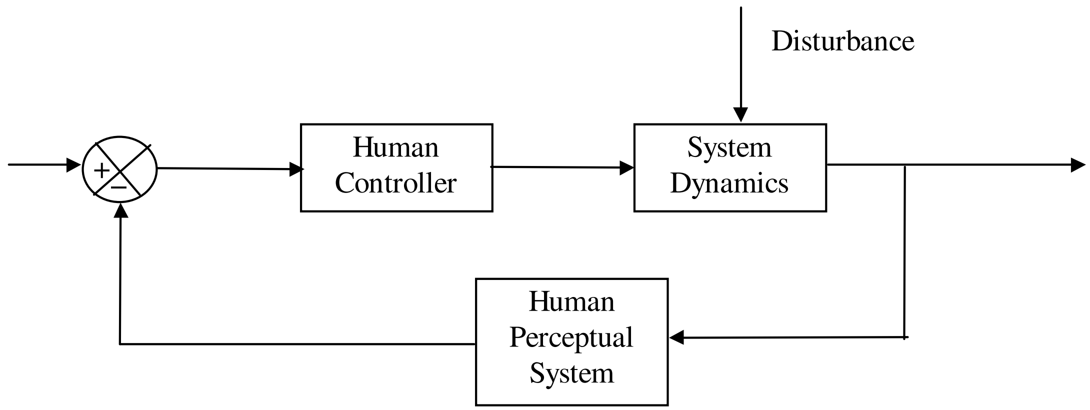


When Art Howe of the Houston Astros swings at a pitch, his body moves in intricate balance, responding to a complex set of orders initiated by the eyes. Visual messages trigger a chain reaction that coordinates muscles and mind. Signals from the eyes speed along the optic nerves to the visual cortex. Some of these impulses travel through the pons to the cerebellum, which helps control fine movements. Linking with other signals in the thalamus, these impulses reach the motor cortex and frontal association cortex and are swiftly relayed to the spinal cord. The spinal cord, in turn, sends messages to the muscles, setting the body in practiced, well-

Hand-eye Interaction (from Sheridan and Ferrell, 1974)



Vehicle Dynamics & Control

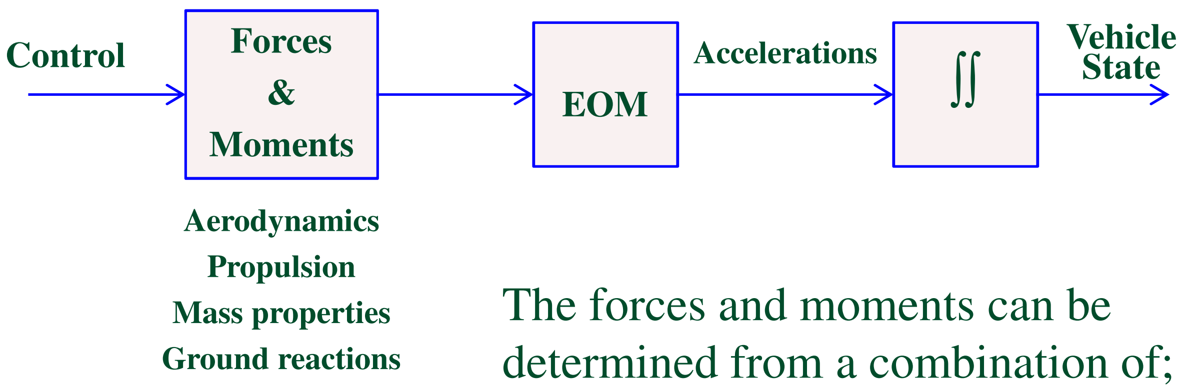


MAN-MACHINE SYSTEM BLOCK DIAGRAM

Vehicle Dynamics Simulation

- Newton's Laws
  - Inertial forces + Applied forces = 0; for equilibrium ie trim
    - F=Ma
    - Applied forces (Aero, Weight, Prop, Ground interact, etc.)
  - Solve for acceleration
    - Integrate for velocity
    - Integrate for position
  - Defining the aero forces & moments for a particular airplane throughout the envelope is **THE** problem.

Vehicle Dynamics Simulation Flow



The forces and moments can be determined from a combination of;

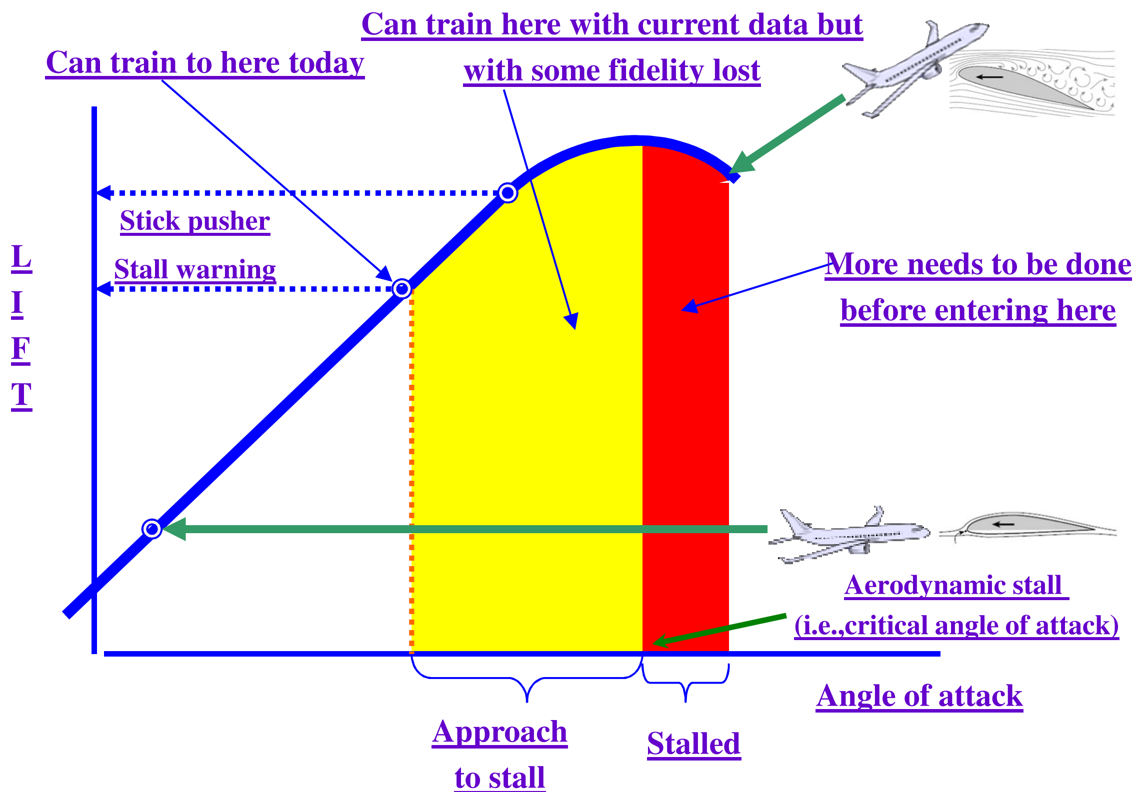
--- Flight testing

--- Wind tunnel testing

--- Theory

Difficult Data Acquisition Problem

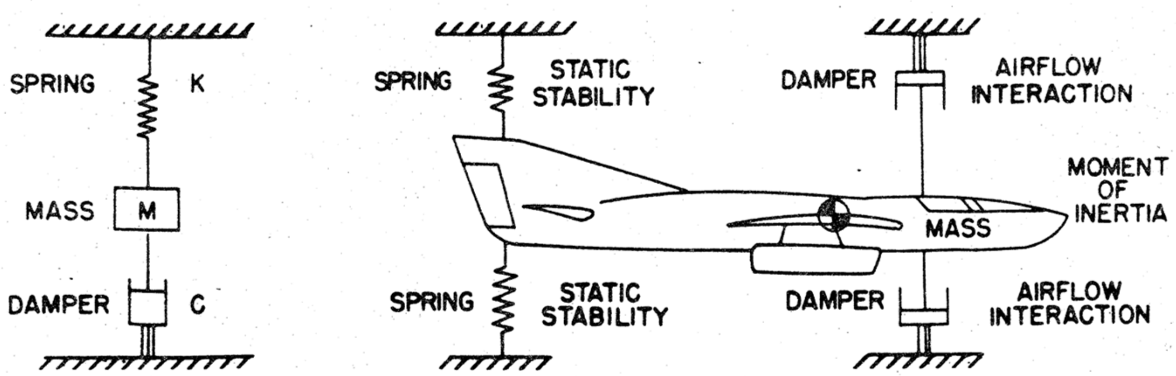
Stall Training



AIRPLANE in FLIGHT

analogous to

SPRING-MASS-DAMPER System



Ref. Galloway 2007

System Dynamics

$$m\ddot{x} + c\dot{x} + kx = kf(t)$$

$$\ddot{x} + \frac{c}{m}\dot{x} + \frac{k}{m}x = \frac{k}{m}f(t)$$

$$let\ \frac{k}{m} = \omega_n^2\ \&\ \frac{c}{m} = 2\varsigma\omega_n$$

$$\ddot{x} + 2\varsigma\omega_n\dot{x} + \omega_n^2 x = \omega_n^2 f(t)$$

- m – mass
- c - friction coefficient
- k – stiffness
- ω – natural frequency
- ς – damping ratio

Simulation of a Dynamic System

$$\ddot{x} + \frac{c}{m}\dot{x} + \frac{k}{m}x = \frac{k}{m}f(t)$$

Solve for Acceleration

$$\ddot{x} = \frac{k}{m}f(t) - \frac{c}{m}\dot{x} - \frac{k}{m}x$$

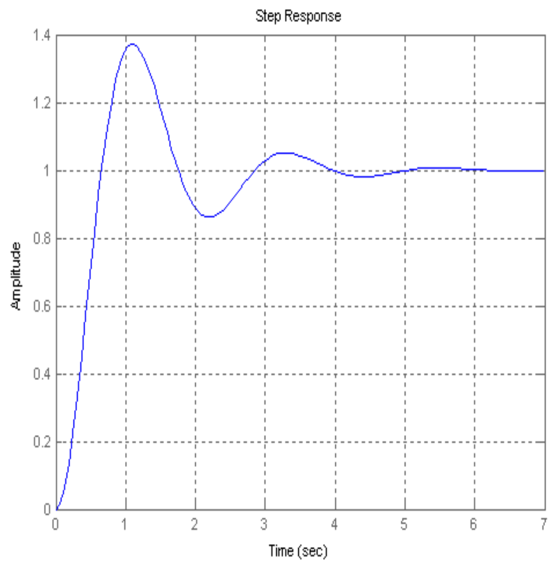
Integrate to obtain *Velocity*

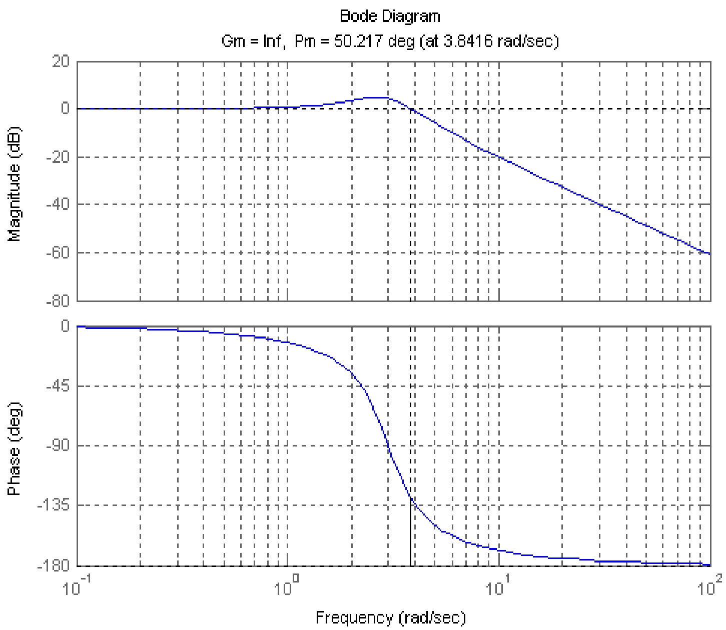
$$\dot{x} = \int \ddot{x}dt$$

Integrate again for *Position*

$$x = \int \dot{x}dt$$

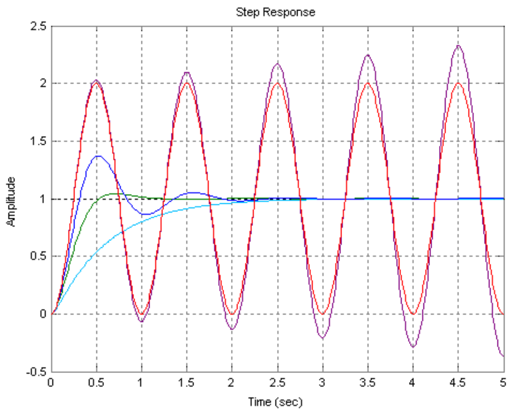
Response in the Time and Frequency Domains

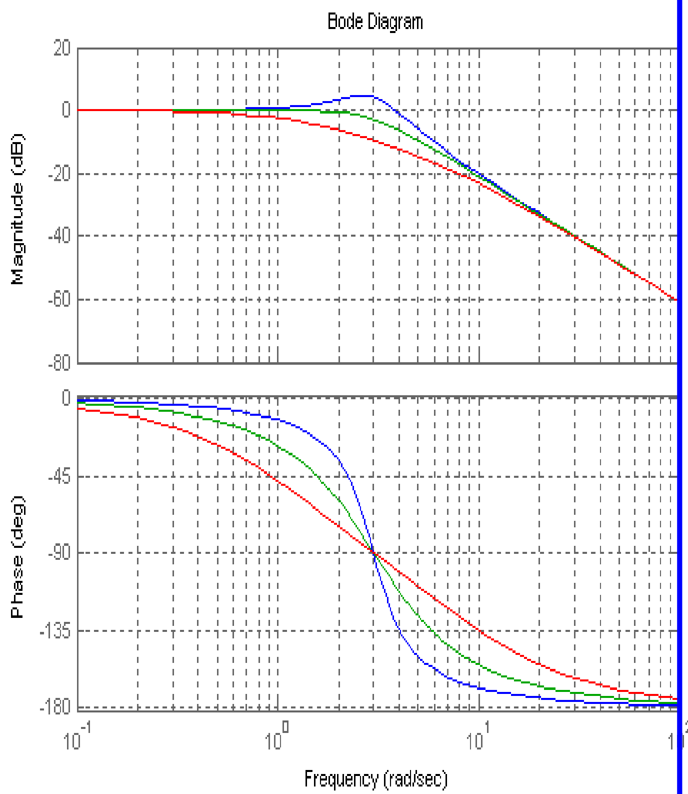




Time and Frequency Responses for Various Damping Ratios

Man-Machine Systems Laboratory





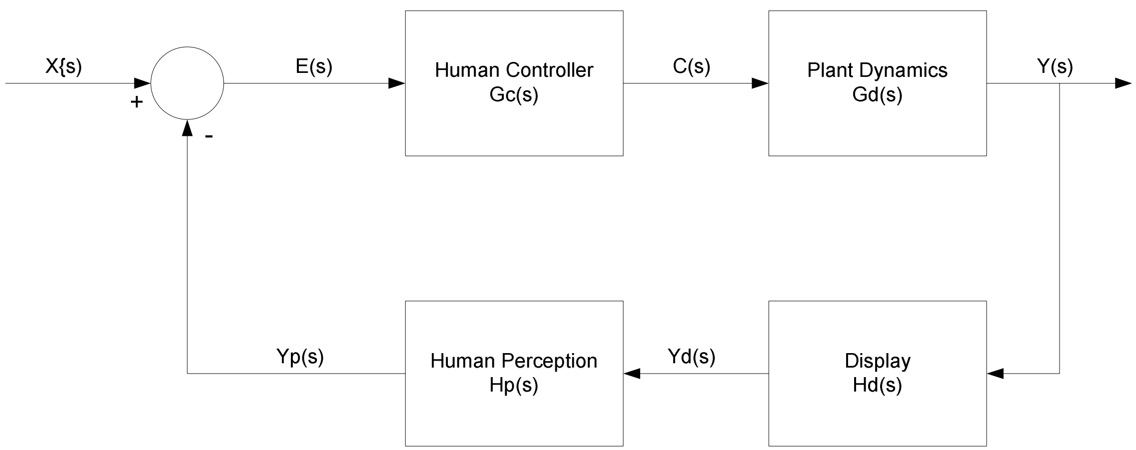
Question!!

How do we characterize this human centered system using a control theoretic approach???

Why do we want to do this anyway??

If we can characterize the system then we can analyze it and predict the effect of various aspects of the simulator on operator behavior!

Human Controller Block Diagram



Human Operator Models

AKA

Pilot Models

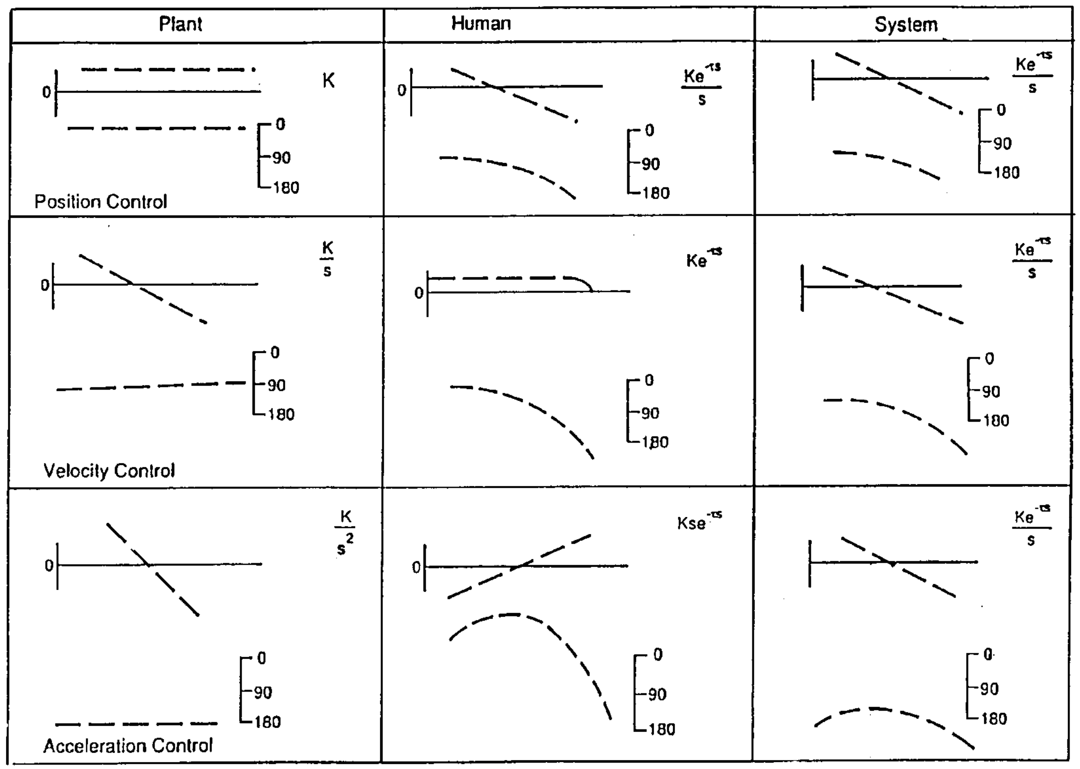
APPROACHES TO HUMAN OPERATOR MODELING

- Crossover Model
- Intuitive Models
- Structural Models
  - Isomorphic model
  - Hess & Modified Hess Models
  - Hosman Model
- Algorithmic Models
  - Kalman Filter Model
  - Optimal Control Model
- Fuzzy / Neural / Genetic Models

CROSSOVER MODEL

- Developed by Duane McRuer.
- Predicts that in the area of the crossover the human will adjust to different plant dynamics to yield the same human plus plant dynamics.
- Human will attempt to force the system to crossover between 3 and 6 rad/sec with a phase margin of 25 to 45 degrees.

The Crossover Model
Illustrated with Three Plants



Intuitive Human Operator Model

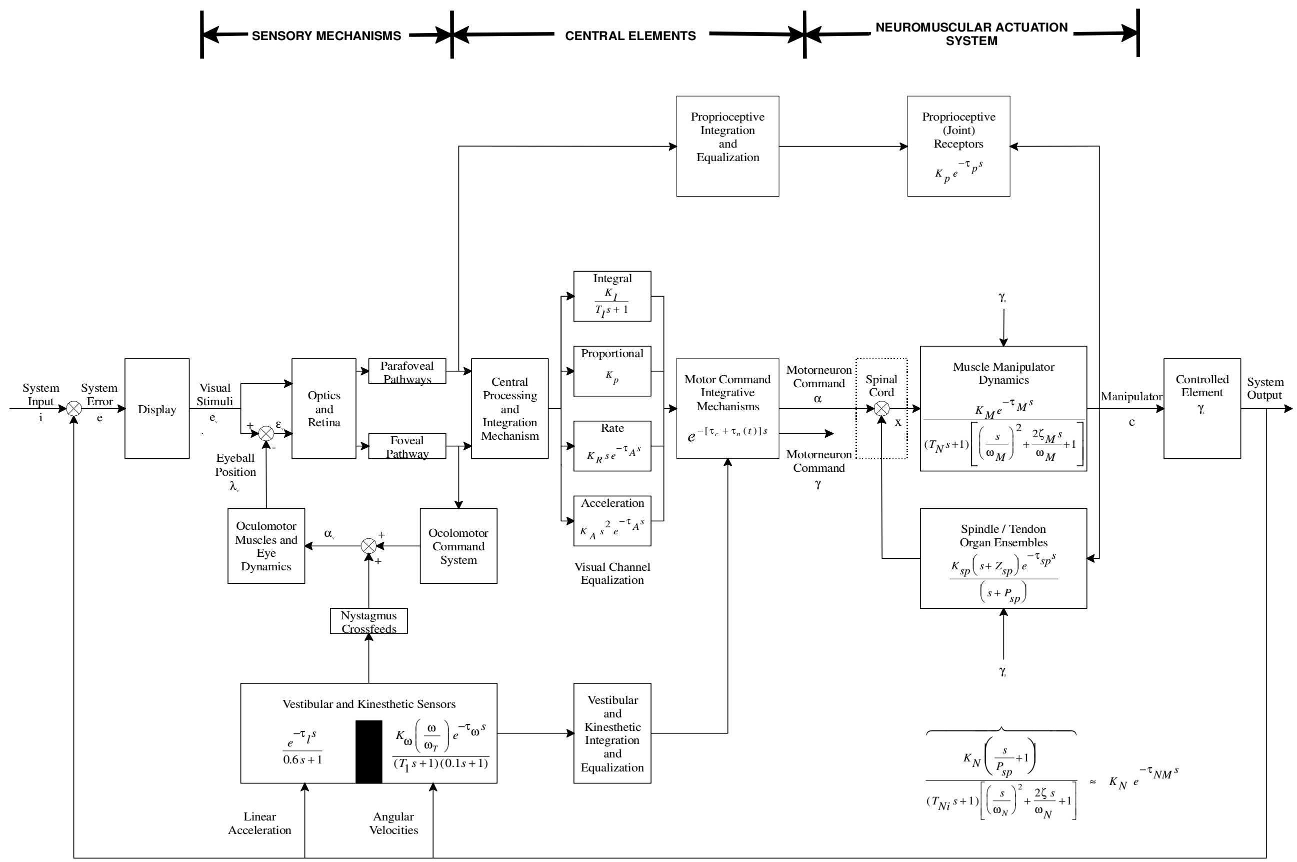
Reaction time delay: $e^{-\tau_d s}$ where $\tau_d = 0.15s$

Gain: $2 \le K \le 20$

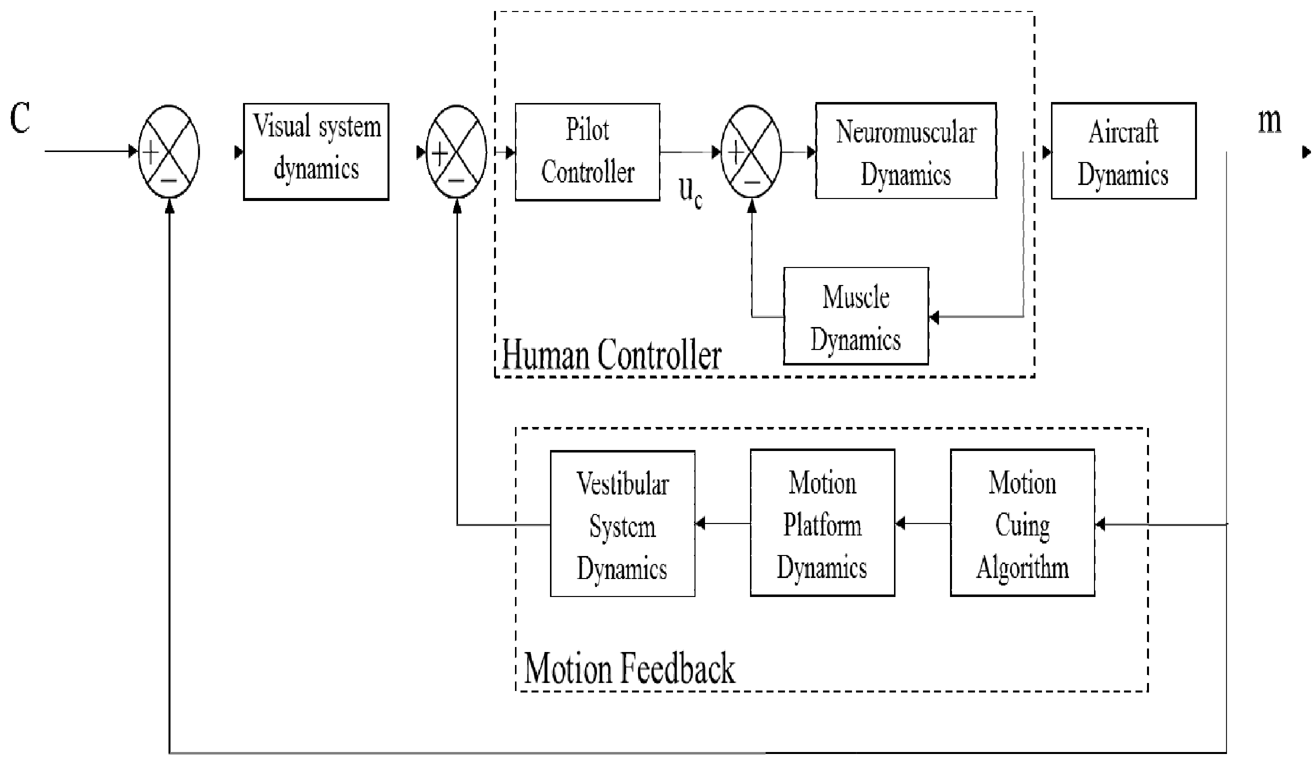
Neuromuscular lag: $\dfrac{1}{\tau_n s + 1}$ where $.1 \le \tau_n \le .2$

Human operator: $\mathrm{Y_H} = \dfrac{K e^{-\tau_d s}}{\tau_n s + 1}$

Structural Isomorphic Model

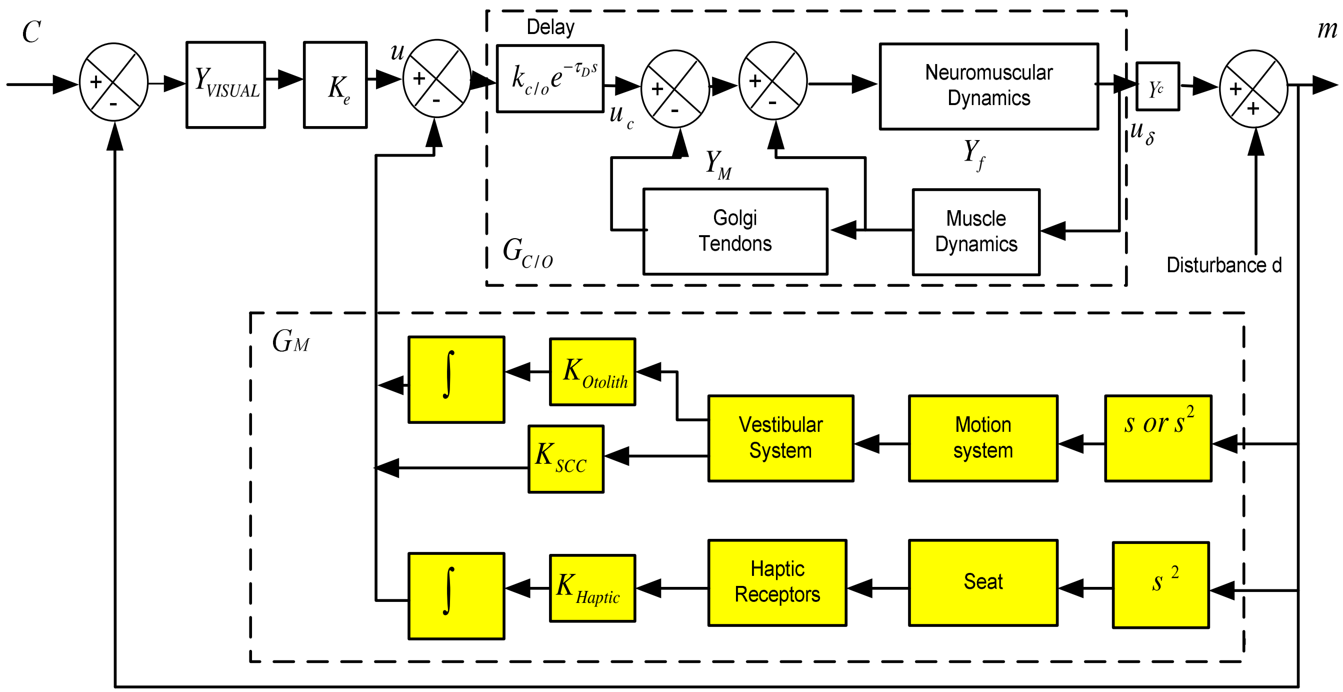


Expanded Human-in-the-Loop Diagram

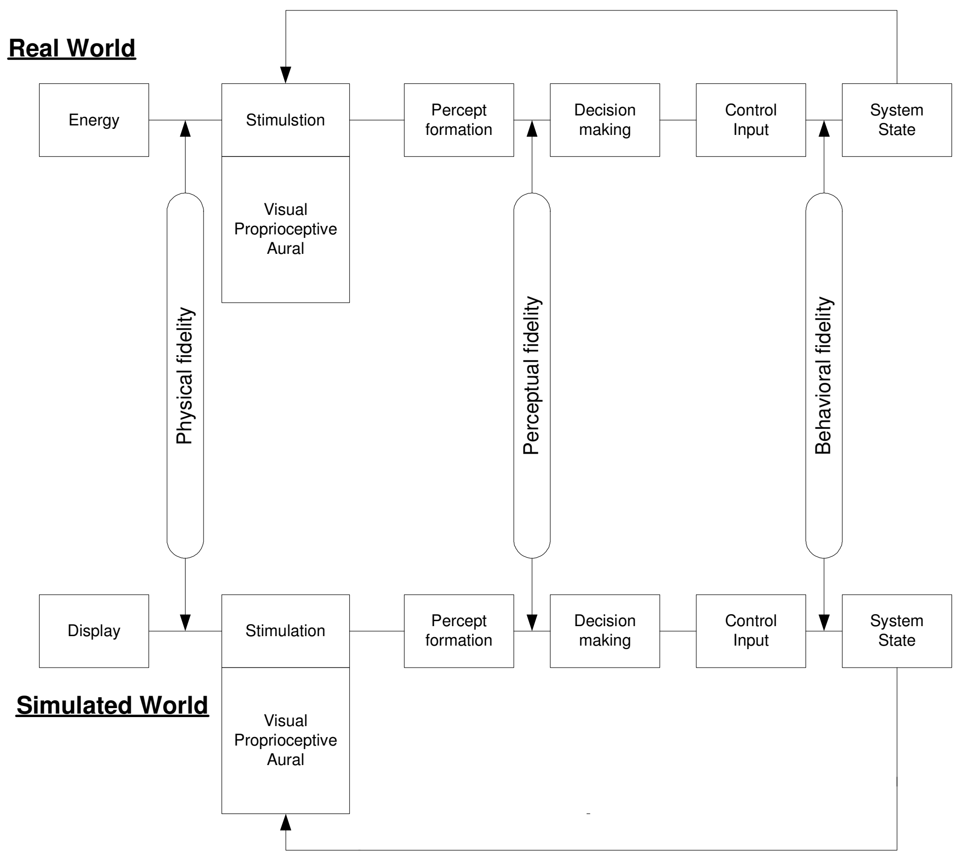


Hess Structural Model

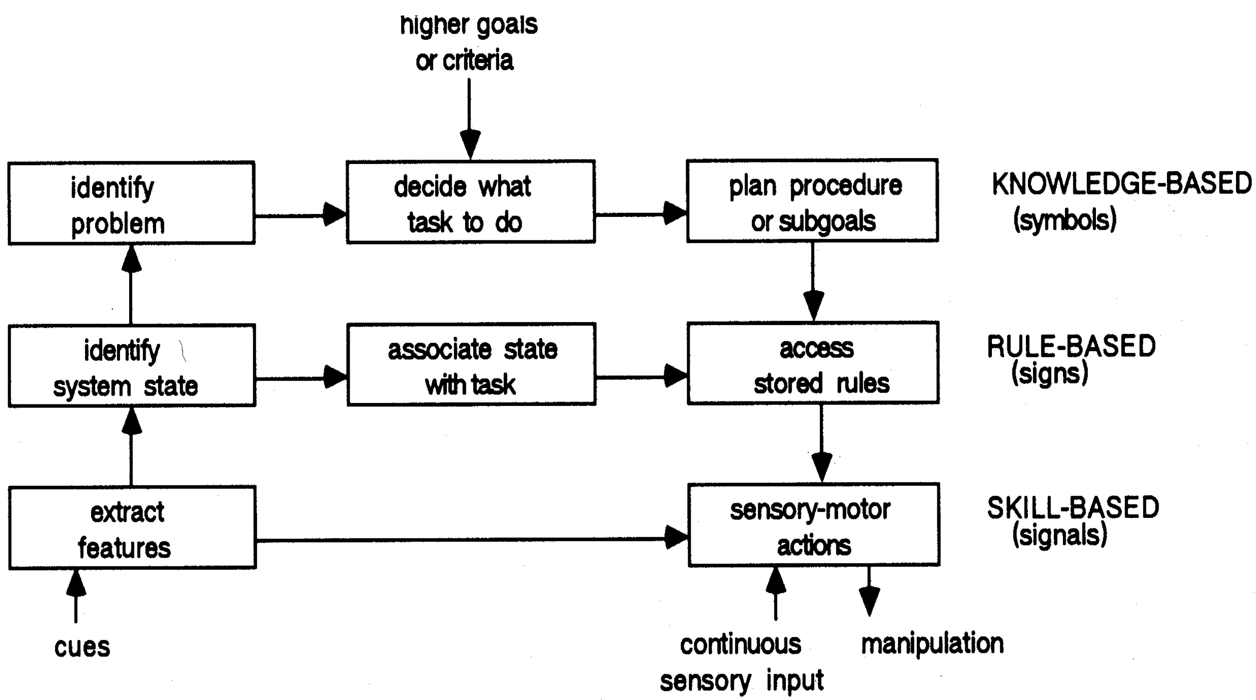
A s modified by George and Cardullo



Simulation Fidelity Concept



Rasmussen's Model for Levels of Human Behavior (Ref. Sheridan, 1992)



TRAINING SIMULATORS

- Aircraft
  - Military
    - Procedures trainers
    - Part task trainers
    - Operational flight trainers
    - Weapons and tactics trainers
    - Maintenance
  - Civil
    - Airplane Simulators Level A-D
    - FTD - Level 1-7
    - Part task trainers
    - Maintenance
    - PC based
- Ground Vehicle
  - Automobiles
  - Buses
  - Trains
  - Trucks
  - Heavy Equipment!!!
- Other
  - Medical
  - Industrial
  - Education

TECHNICAL CHALLENGES

- System Dynamic Modeling
- Real Time for Most Applications
- Visual Environment
  - Resolution
  - Brightness
  - Field of View
  - Scene Density
- Motion and Force Environment
  - Frequency and time response
  - Smoothness
  - Uncommanded cross-coupling
- Temporal Distortion
  - Throughput Delay
  - Communication Delay
  - Phase Lag
- Cyber Sickness
- Networking Simulators

Flight Simulators

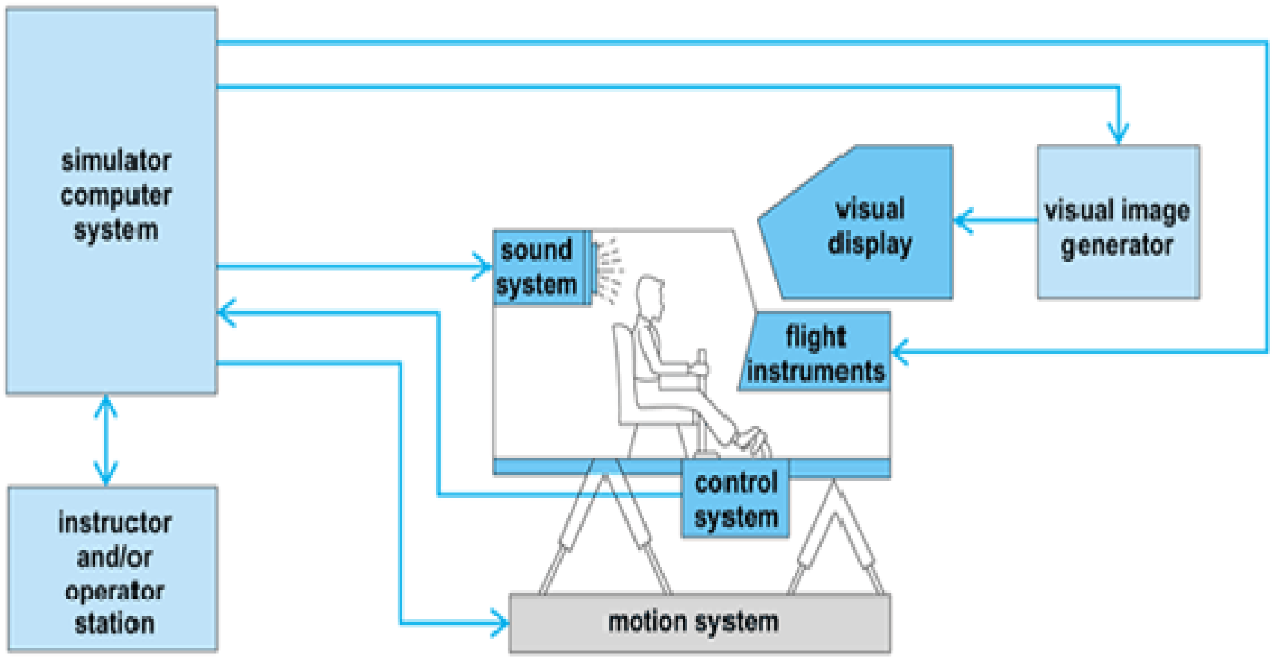
Architecture

&

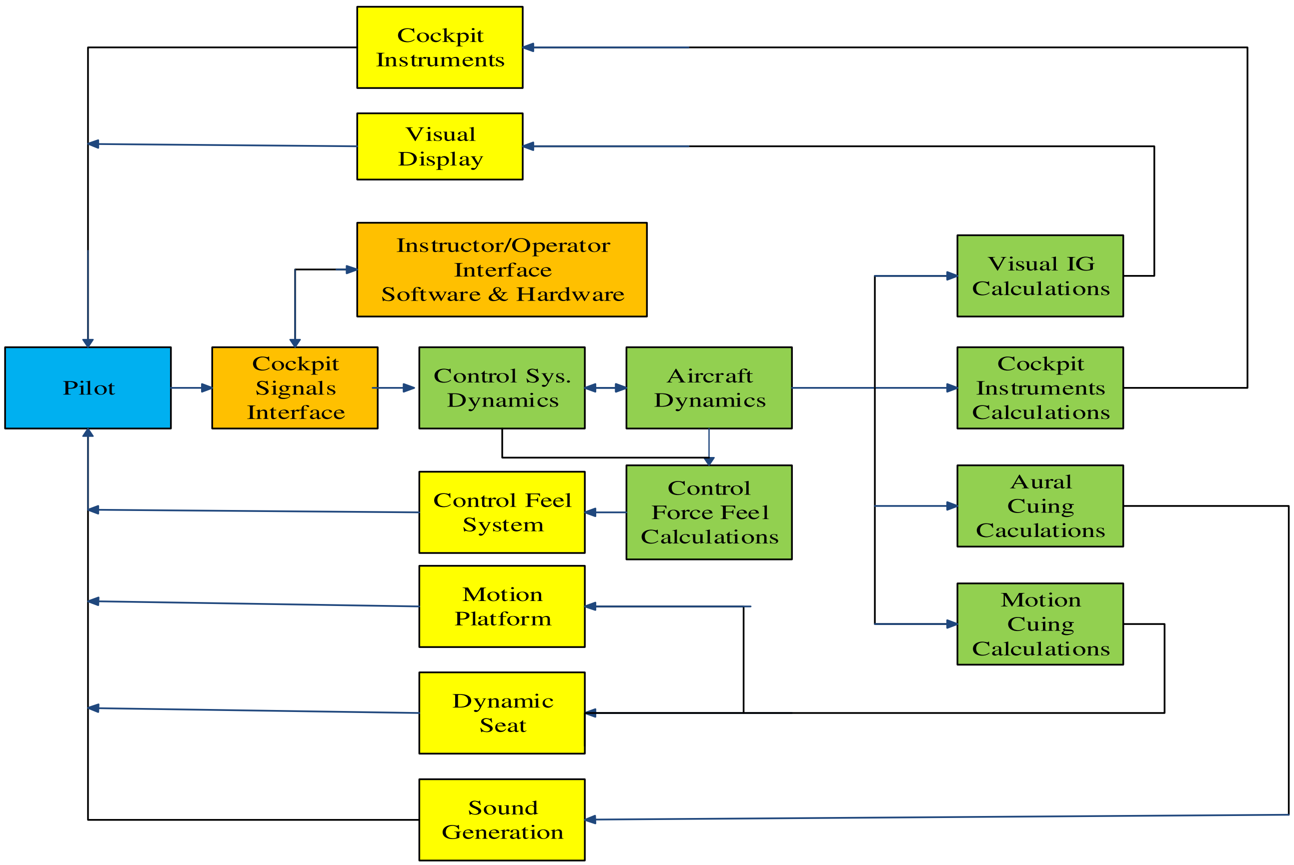
Overview

Much more on this throughout the week

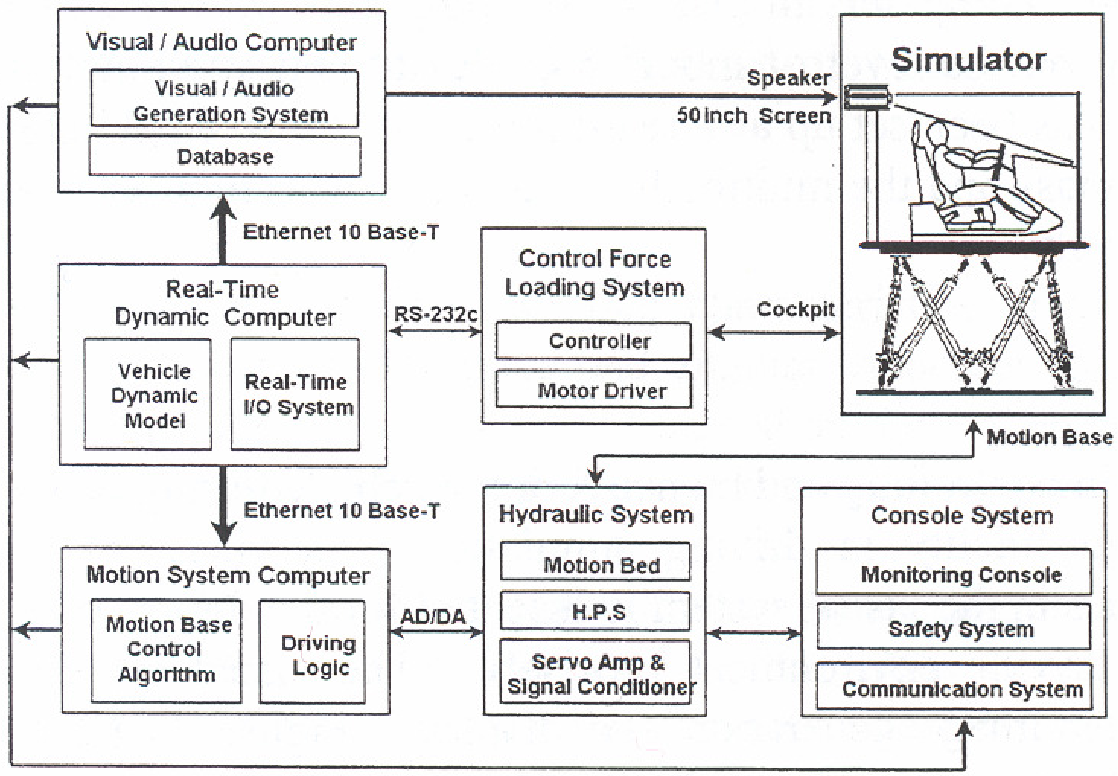
Flight Simulator Architecture



Simplified Simulation Block Diagram



Simulator Architecture



Simulator Systems Hardware

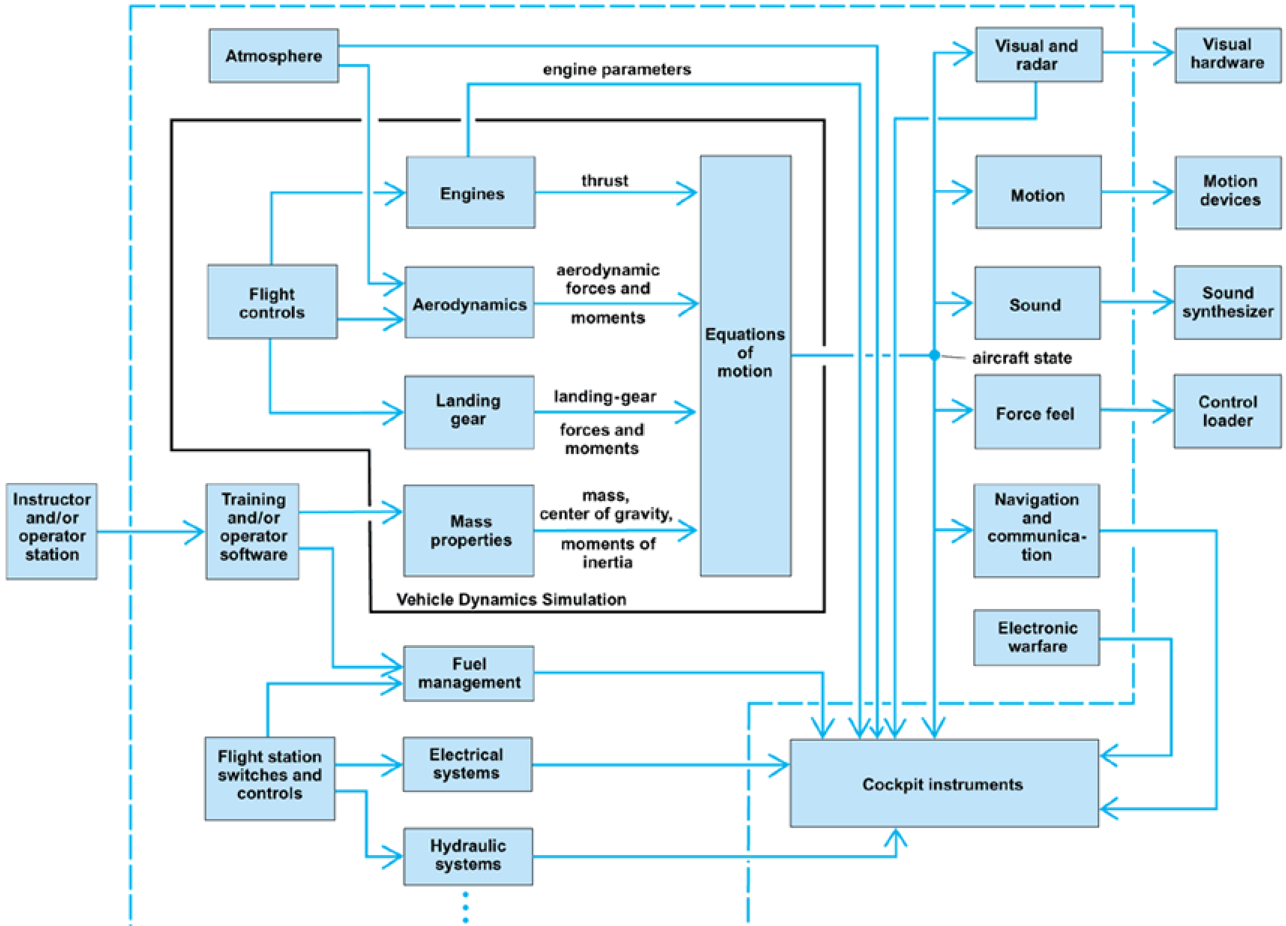
- Computer
- Crew Station
- Image Generator
- Display System
- Motion Cuing Devices
- Control Force Cuing Device
- Instructor/Experimenter Station
- Facility
- Sound System
- Communications System
- Avionics Processors

Simulator Systems Software

- Computer System
- Mathematical Models (Vehicle Dynamics, Etc.)
- Visual/Sensor/Threat Data Bases
- Image Generator
- Motion Cuing Algorithms
- Control Force Feel Models
- Aural Cuing Models

Simulator Systems Math Models

- Vehicle Dynamics
- Control Systems
- Vehicle Systems
  - Electrical Power
  - Navigation
  - Communication
  - Vehicle Instruments
  - ECS
- Sensor Systems
- Environment
  - Atmosphere
  - Weather
  - Scenario
- Electronic
  - Warfare Systems
  - EMR
  - Acoustics

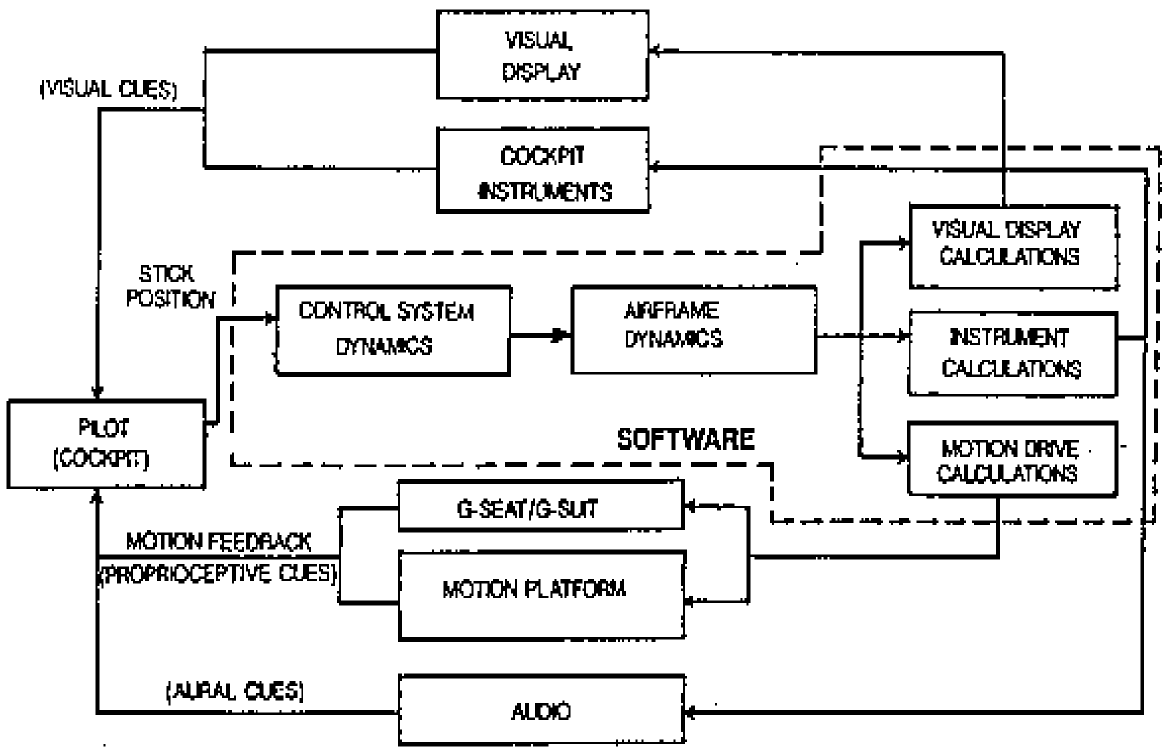


Atmosphere
engine parameters
Visual and radar
Visual hardware
Engines
thrust
Motion
Motion devices
Flight controls
Aerodynamics
aerodynamic forces and moments
Sound
Sound synthesizer
Equations of motion
aircraft state
Landing gear
landing-gear forces and moments
Force feel
Control loader
Instructor and/or operator station
Training and/or operator software
Mass properties
mass, center of gravity, moments of inertia
Navigation and communica-tion
Vehicle Dynamics Simulation
Electronic warfare
Fuel management
Flight station switches and controls
Electrical systems
Cockpit instruments
Hydraulic systems

Vehicle Dynamics Packages

- **Air vehicles**
  - DatCom
  - Microsoft Flight Simulator
  - X-Plane
  - Flightgear
- **Ground vehicles**
  - VDANL
  - RTRD
  - DADS (LMS Int.)
  - CarSim
  - Vortex

FLIGHT SIMULATION FLOW



VEHICLE CONTROL SYSTEM SIMULATION

- Control System Characteristics
- Control Feel Systems
  - Electric
  - Hydraulic

Vehicle Controls Simulation

Aircraft

- Primary Controls
- Secondary Controls
- SAS
- AFCS

Ground Vehicle

- Steering
- Throttle
- Braking
- ABS

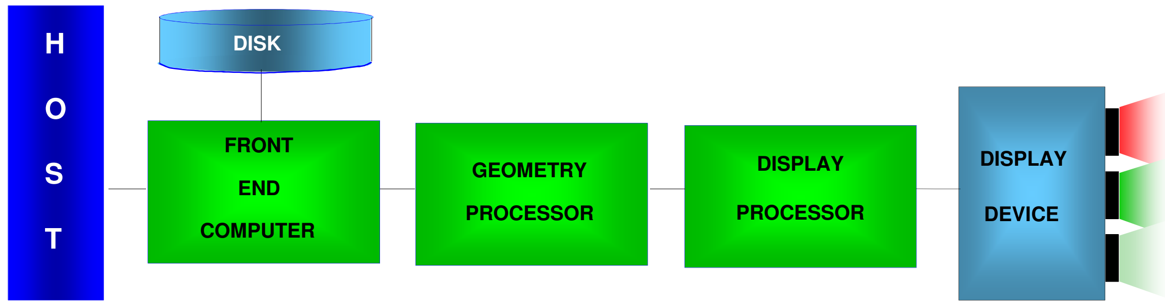
Simulator Computers

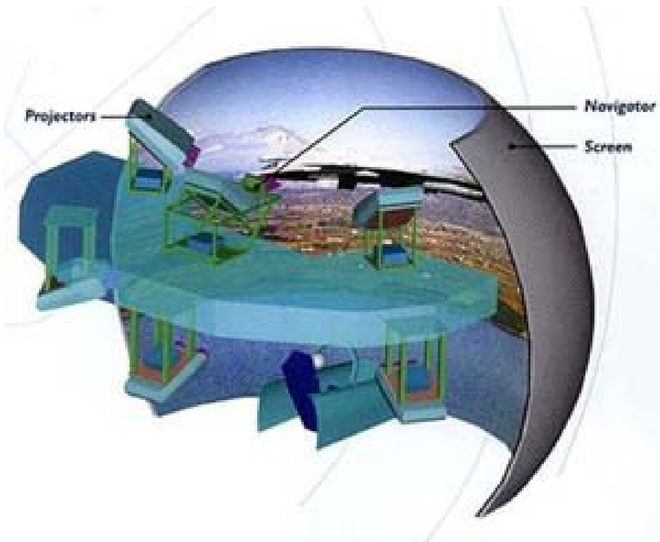
- Host Mini
- Host Main Frame
- Distributed Microprocessors
- Personal Computers
- Special Purpose Systems
- Analog Computers also Possible

Visual Simulation

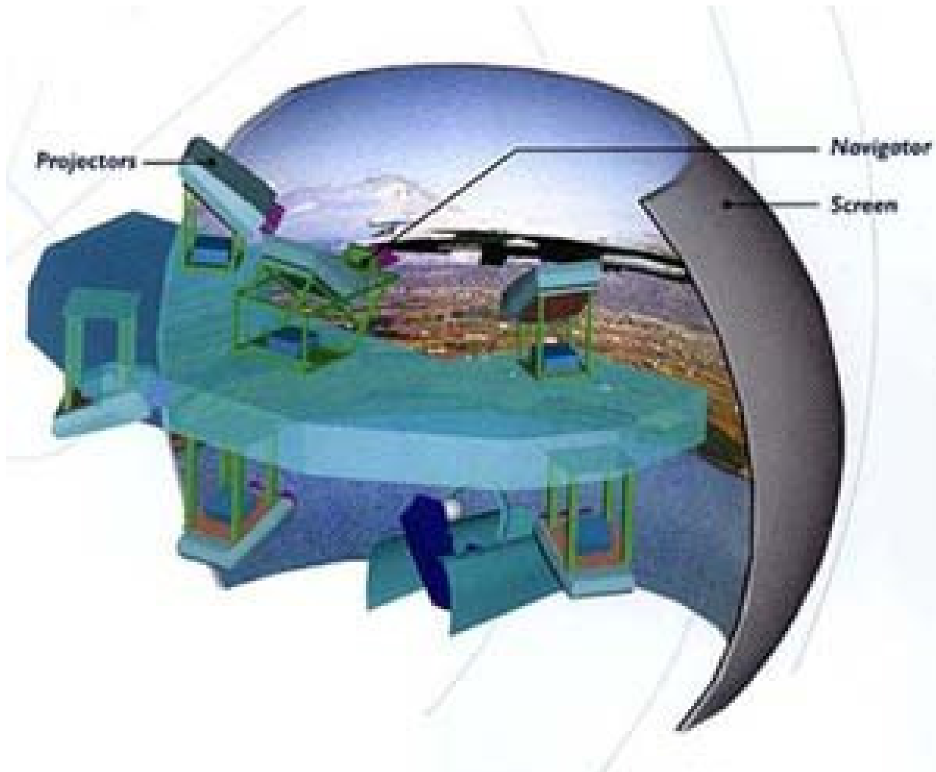
- Architecture
- Image Generators
- Data Bases
- Displays
- Tactical Environment

Typical Visual System Architecture

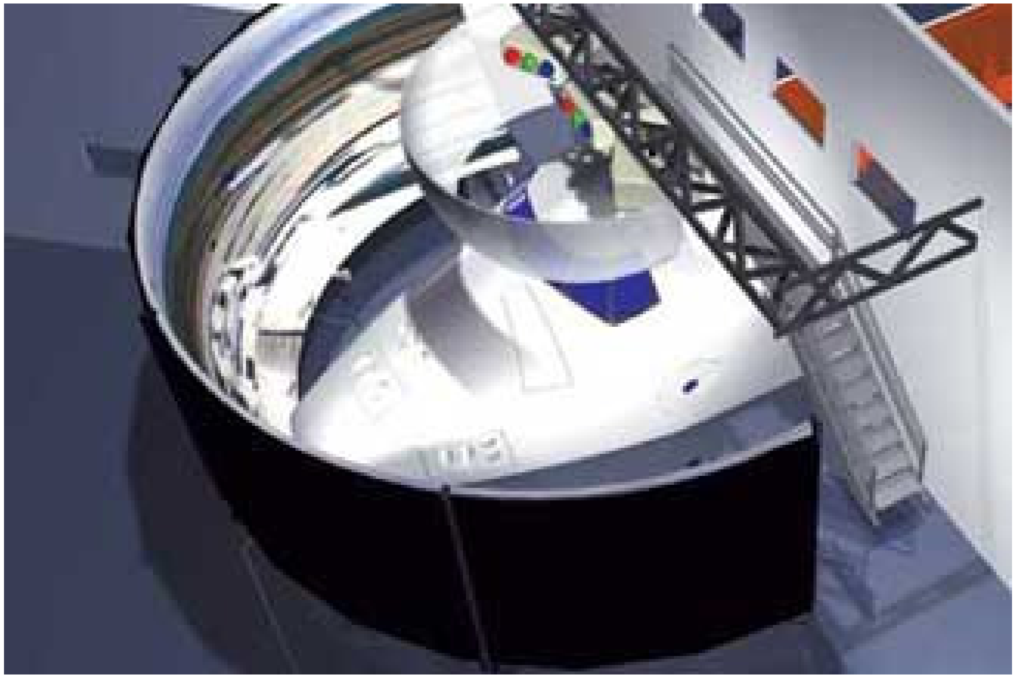




Real Image Projected Display



Projected Collimated Display System



Ship Bridge Simulator

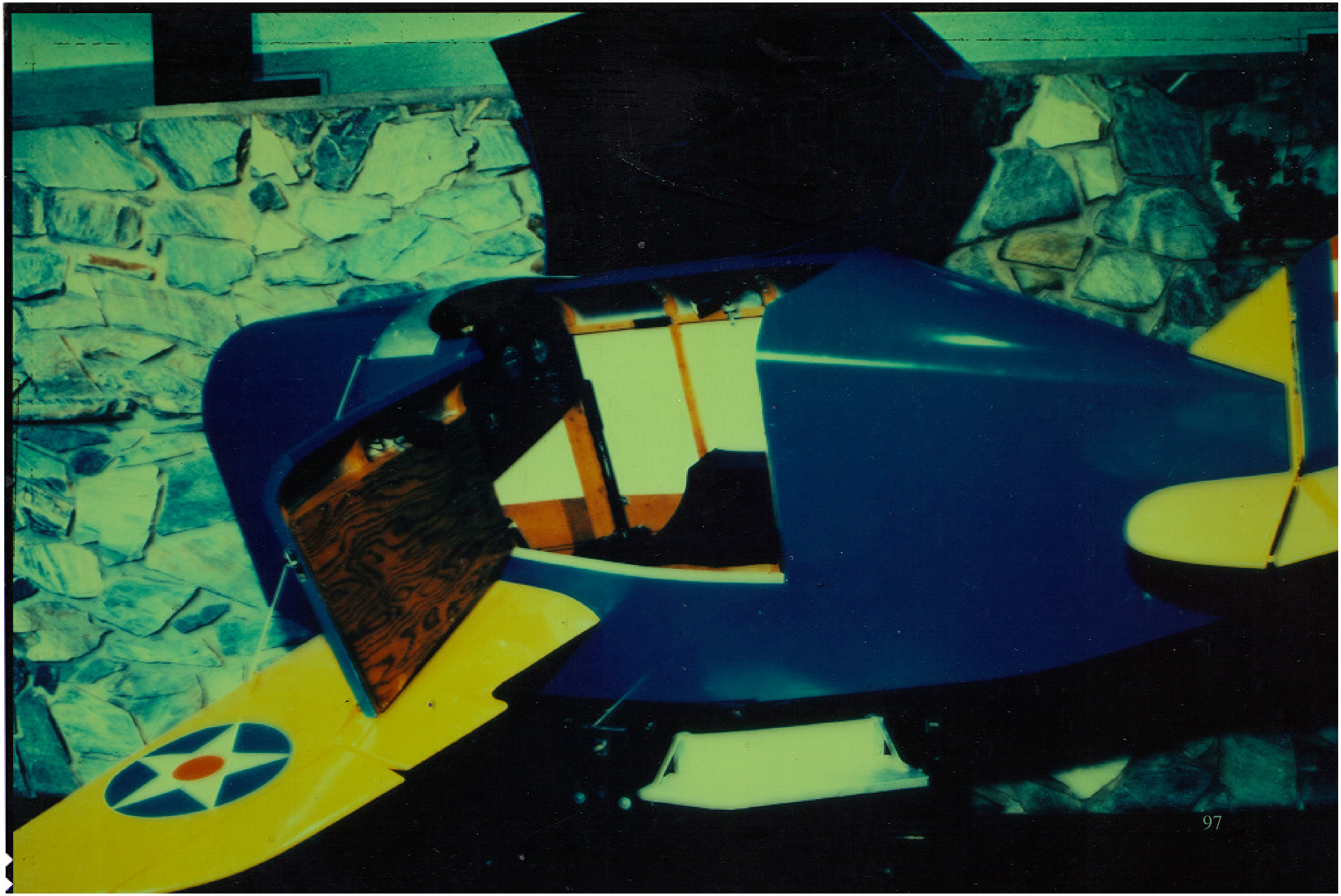
Recent HMD

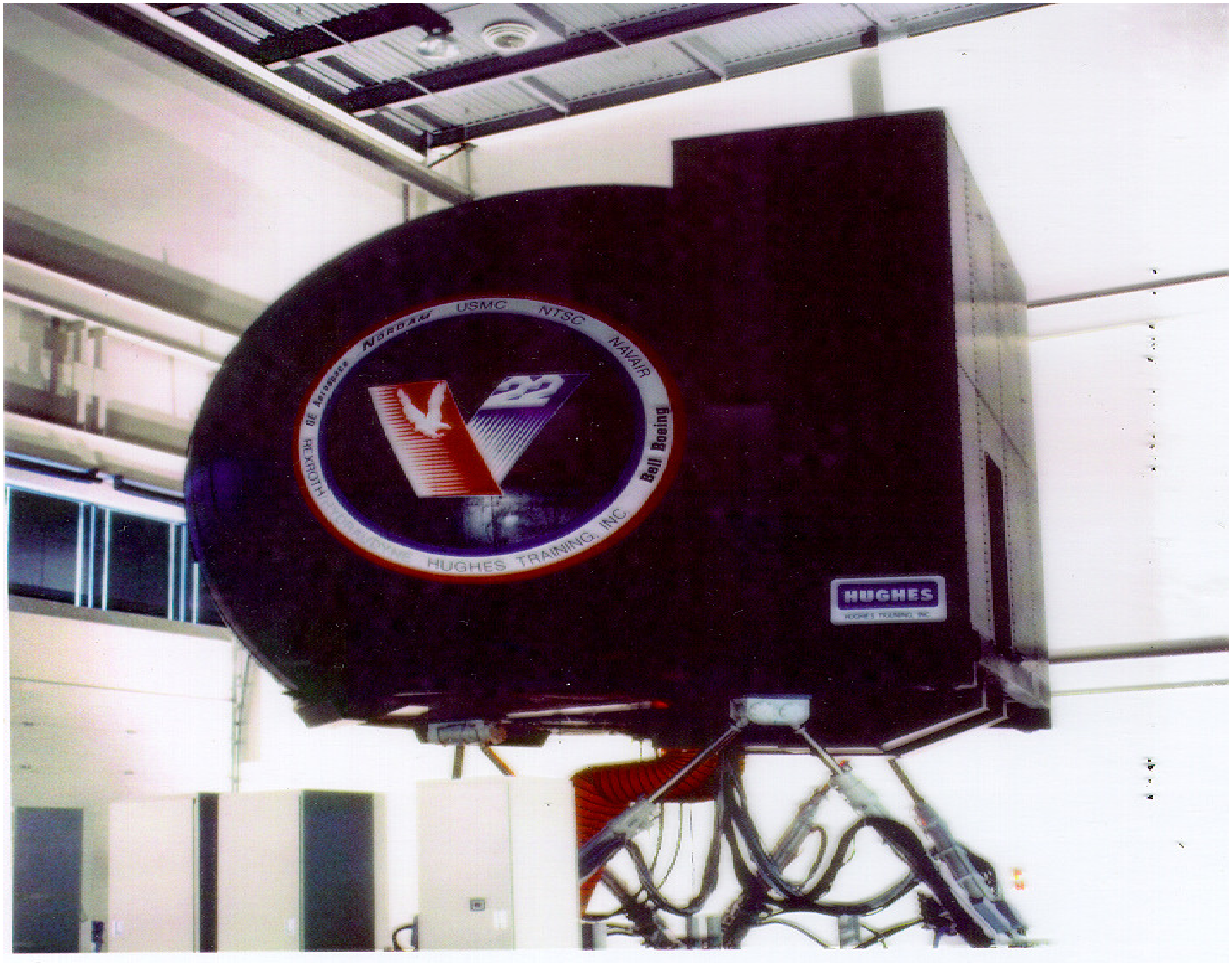
Motion Cuing Systems

- Platform Motion Systems
- Vibration Systems
- Dynamic Seats
- G-Seats
- Anti-G Suits
- Other

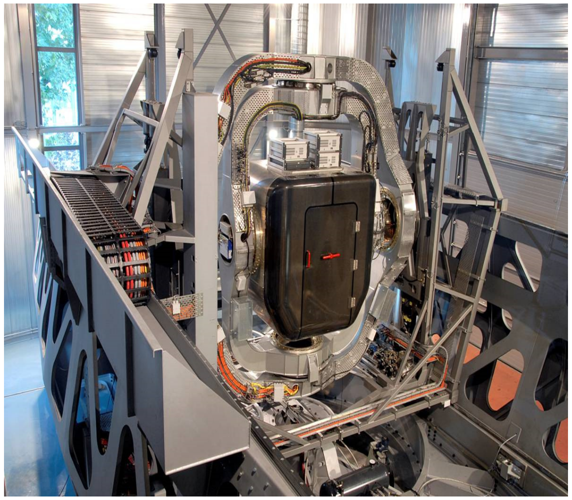
Non-visual motion cues: Are they necessary?

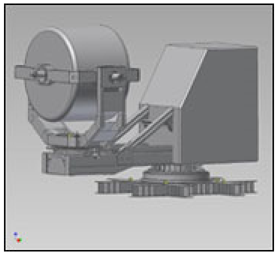
- It depends upon vehicle dynamics
- It depends upon simulation purpose
- It depends upon task

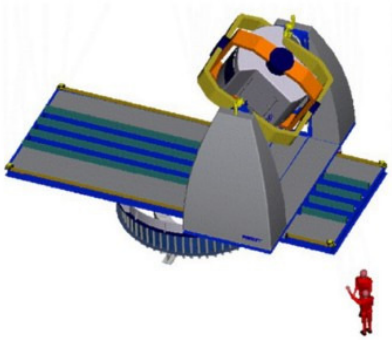



USMC
NTSC
NAVAIR
Bell Boeing
REXROTH
HUGHES TRAINING, INC.
22
HUGHES

Disorientation Devices








PRODAS AcuView
Test Area !
EJECT
SEGS
SEGS

Vehicle Simulator Problem Areas

- Transport delay
- Simulator sickness
- Eye level resolution
- Display systems
- Motion cueing
- Vehicle dynamics – Not all solved

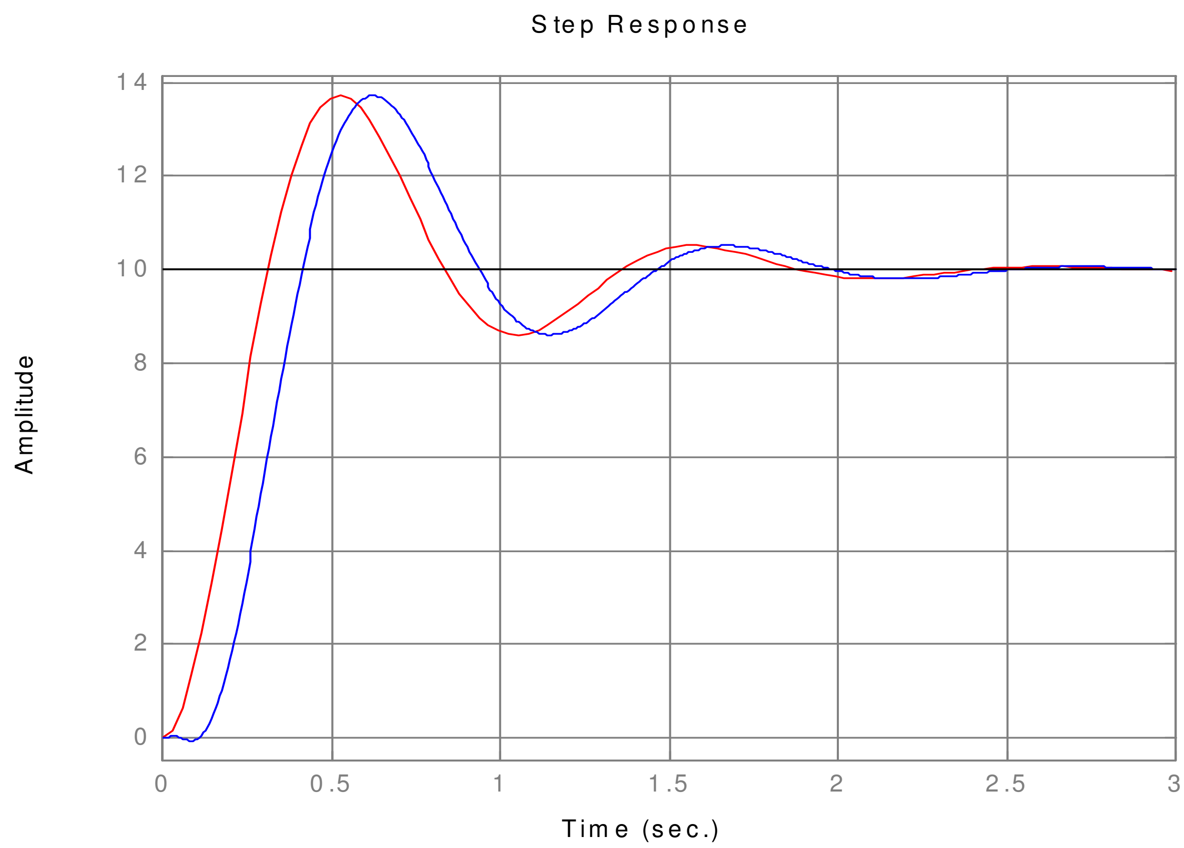
Driving Simulator Issues

- Cuing System Fidelity
- Vehicle Dynamics Modeling
- Roadway & Terrain Representation
- Scenario Control & Authoring
- Data Collection
- Research Adaptability

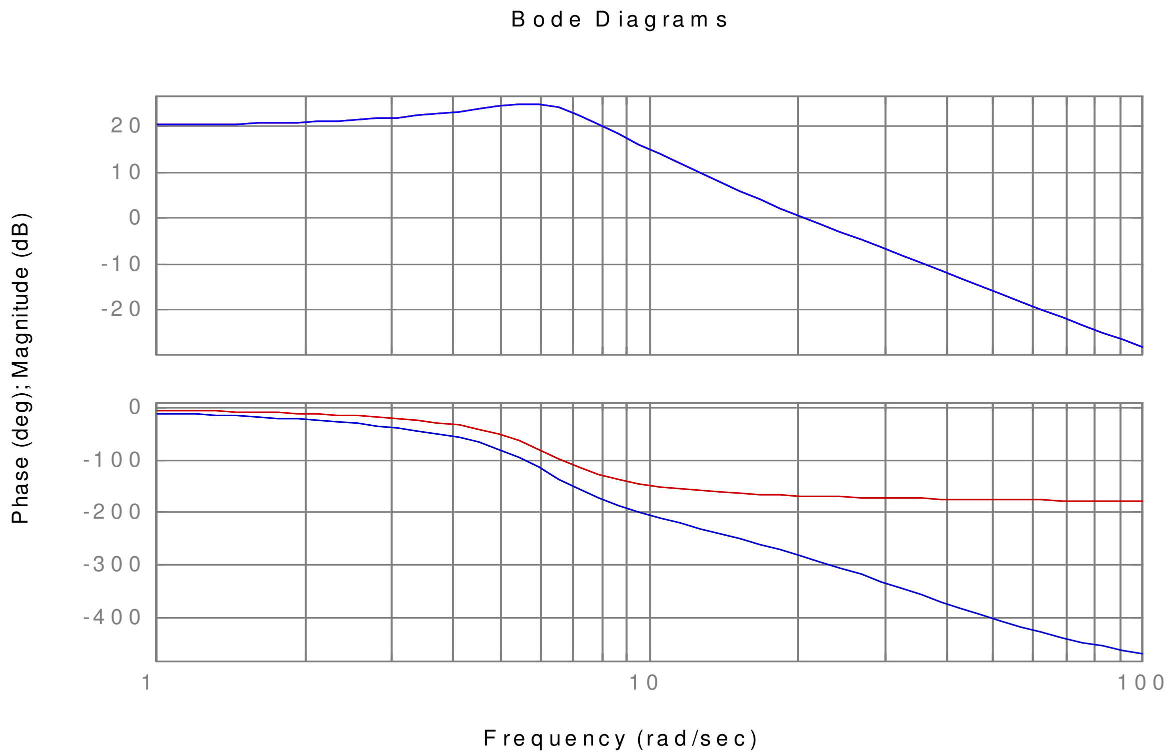
Transport Delay in Simulators

- Operators are most sensitive to phase lag associated with the delay.
- Phase lag is proportional to the delay.
- Maximum tolerable delay is a function of task and system dynamics.
- Delay can be minimized.
- Phase lag can be compensated to some extent.

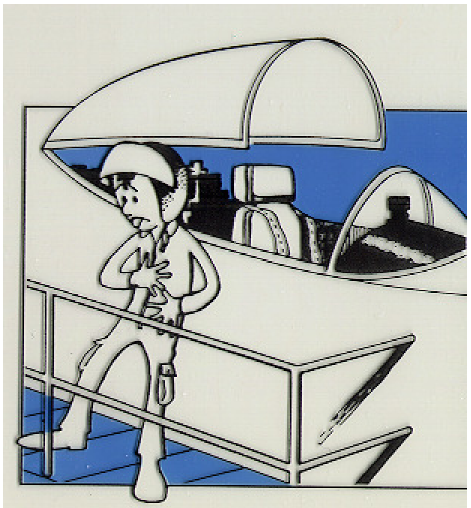
Step Response of System With and Without Delay

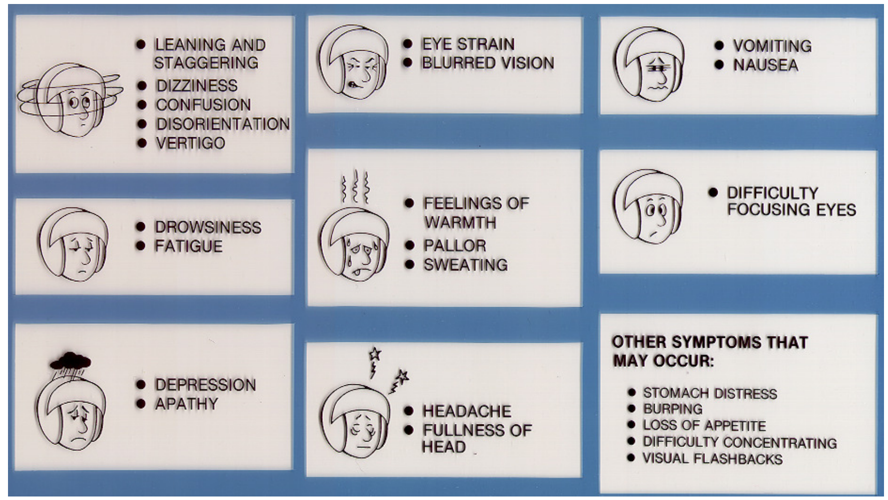


Bode Diagram of System With and Without 100 ms Delay



Simulator Sickness

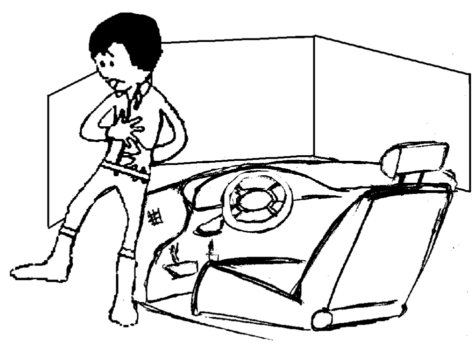




Sickness in simulator, but not in vehicle

Diverse set of symptoms
Some similar to motion sickness

Can occur during or after simulator sessions



Why Is It Of Concern?

- Altered Behavior
- Acceptability of Simulation
- Safety

Summary of Simulation Trends

- Visual
  - Database generation in real-time
  - Correlated databases
    - Visual , FLIR/Radar, Acoustic, Threats
  - Image Generators – becoming commodities?
  - Display Systems – achieve eye limiting resolution
- Motion cueing – Yes or No? – increased bandwidth
- Human Behavior Modeling & Measurement
- Communication Standards Among Simulators
  - High Level Architecture (HLA)
  - Distributed Mission Training
  - Vehicle Dynamics – AIAA M & S Tech. Committee
- Combined forces - Including ground personnel (LVC)
- UAV operator training/research
- Upset recovery and/or prevention training

Examples of Simulators

Civil Transport Flight Simulator

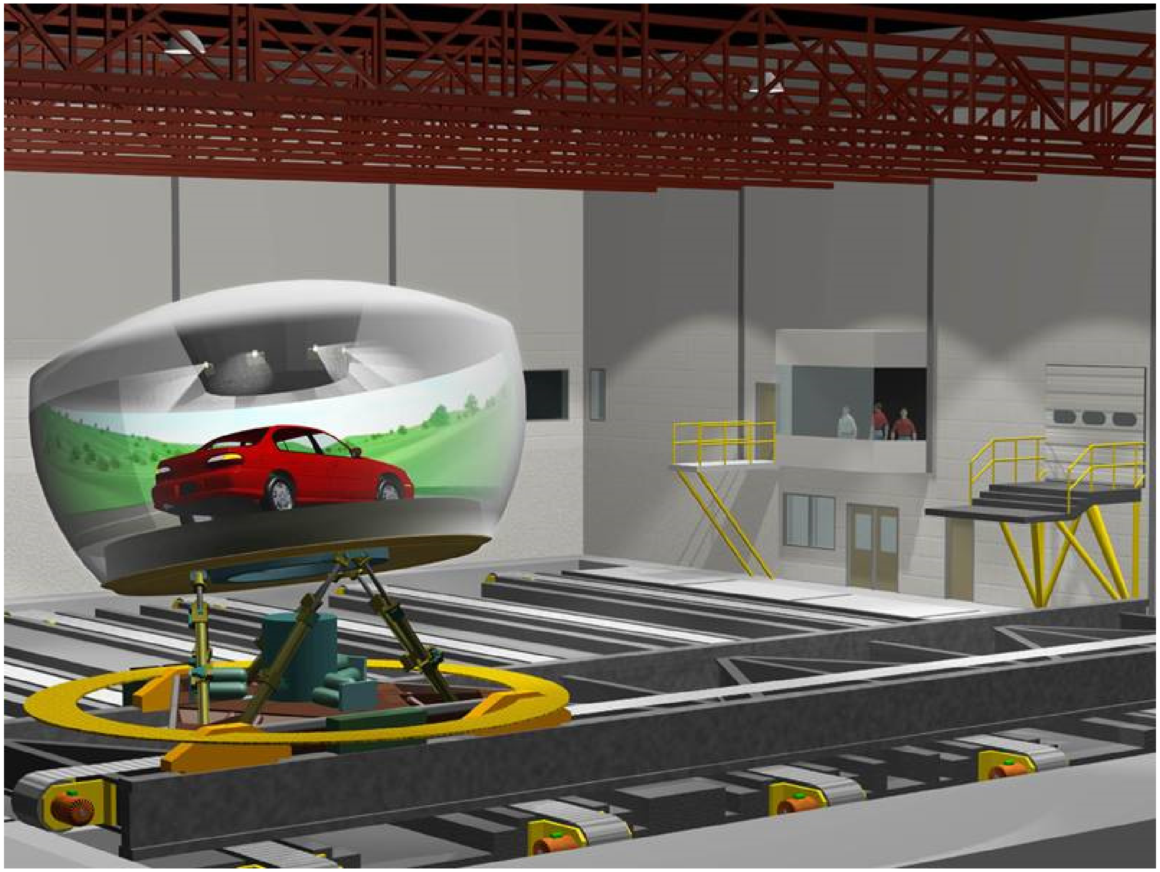
The United States Air Force F-16 Unit Training Device

CAE Air Crew Selection System

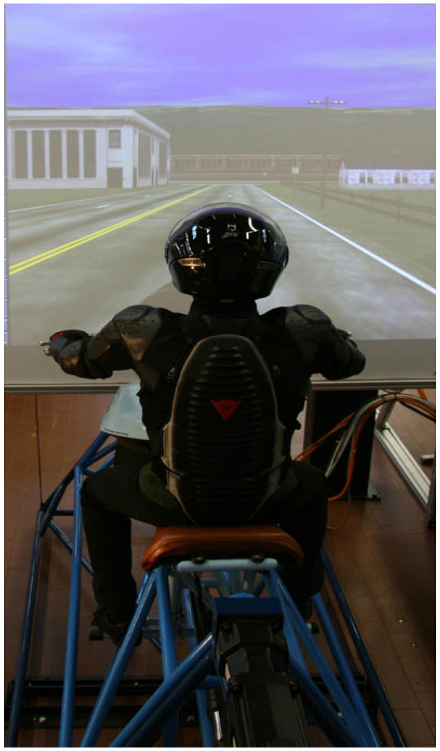
Driving Simulator Applications

- Driver Behavior Studies
- Driver Performance Measures
- Driver Screening & Licensing
- Driver Training
- Vehicle Control Studies
- Vibration & Noise Studies
- Driver Display Development
- Human Factors Evaluations
- Accident Reconstruction and Analysis
- Drug & Alcohol Studies

National Advanced Driving Simulator



Motorcycle Simulator
University of Padua



UAV & Ground Forces Simlators

UAV Simulation - MetaVR

Ground Controller Embedded Simulation

Deployable UAV Training Device

Ground Level Activity

MetaVR generated Baghdad street scene

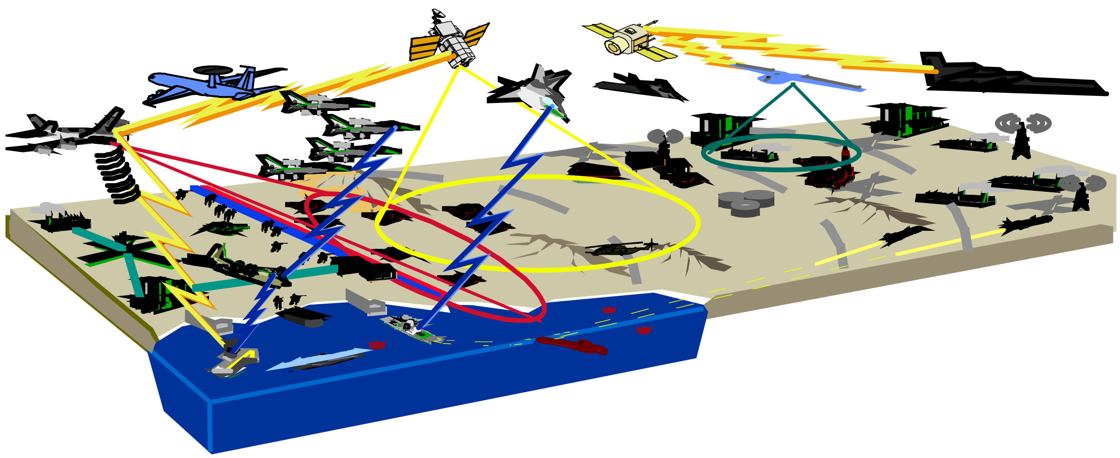
Networked Simulators

Now referred to as LVC

Live – Virtual – Constructive

What does this mean?

Joint Synthetic Battlespace



LVC Problems

- Integration Issues
- Transport Delay
- Fair Fight Issues
  - Visual System Resolution
  - Vehicle Dynamics Modeling
  - Vehicle Systems Modeling (e.g. radar, etc)

Question: Is it worth the effort?

Medical Simulation

- Anesthesiology
- Laparoscopy
- Endoscopic Knee Surgery
- Virtual Organs
- Virtual Endoscopy
- Arachnophobia Treatment
- Acrophobia Treatment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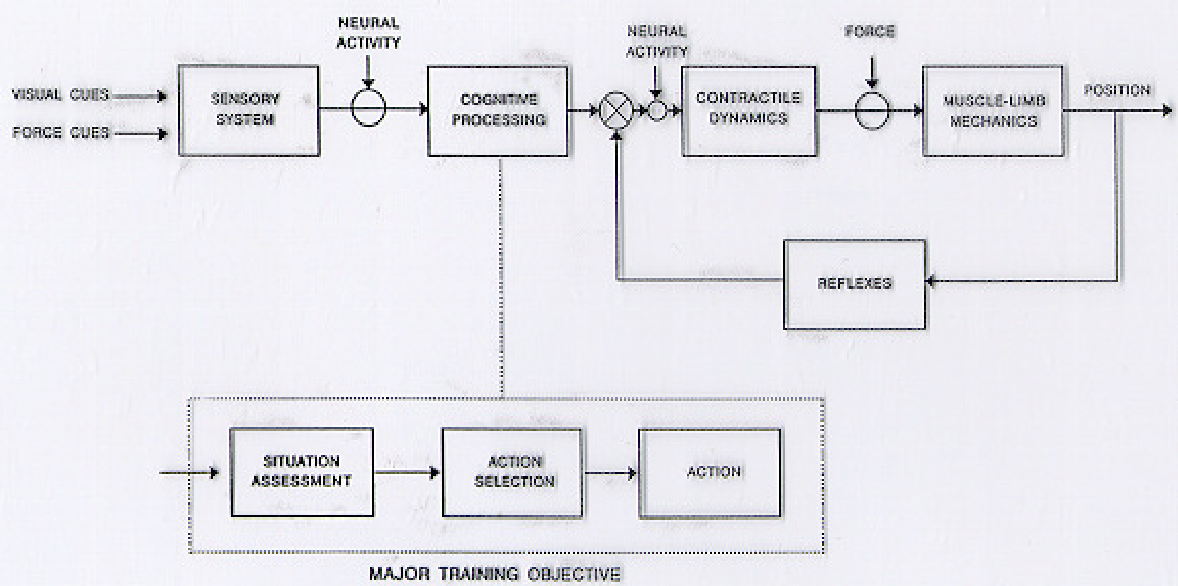
Intuitive Surgical Robot

SURGEON SUBSYSTEM



Break Time!!