Airborne Wind Energy Workshop

23 – 24 May 2012

K.U. Leuven, Optimization in Engineering Center, Belgium

The Rough Way of Making Visions Fly

Lessons Involuntarily Learnt From Controlling Aircraft

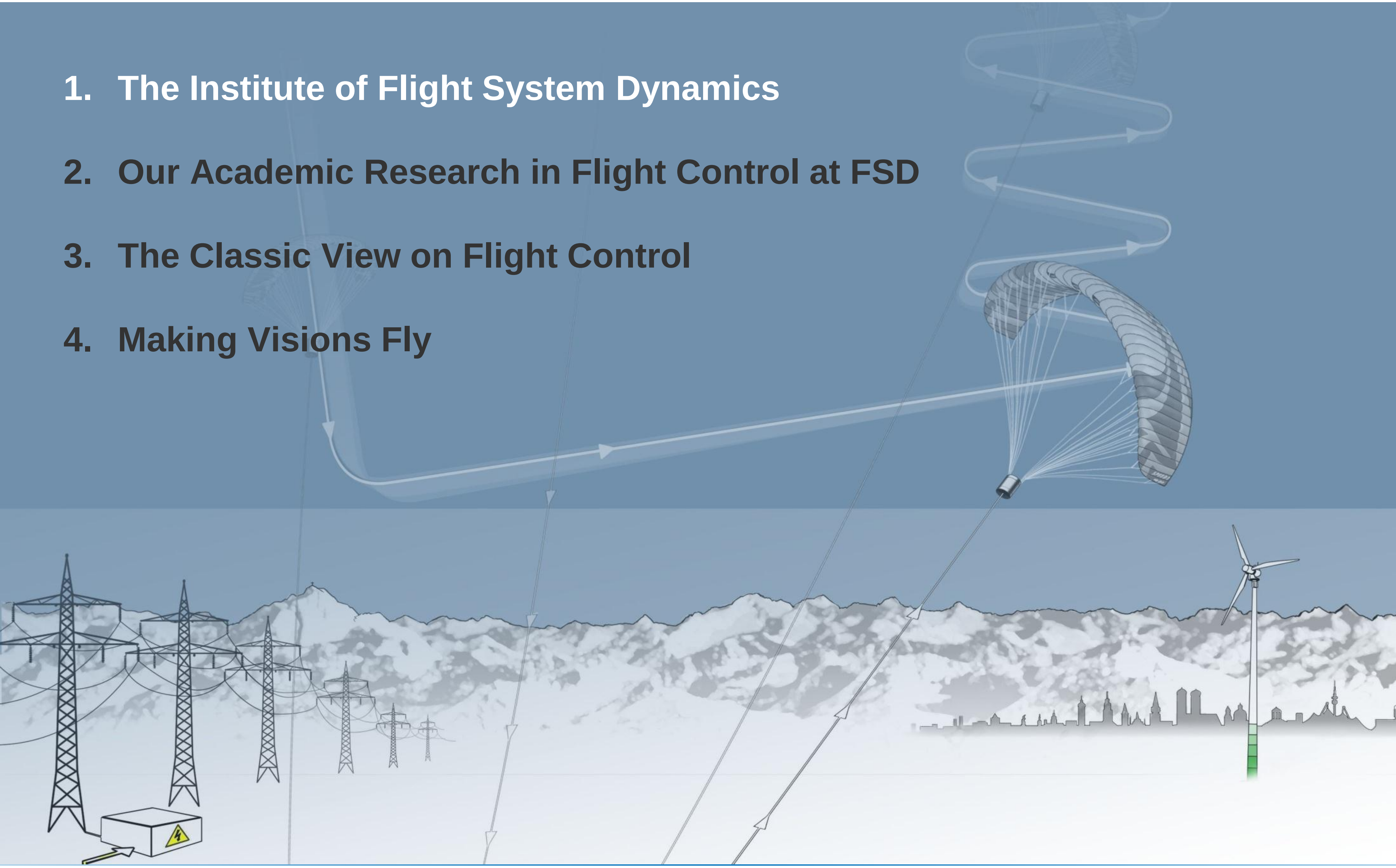
Florian Holzapfel, Patrick J. Lauffs

Institute of Flight System Dynamics, Technical University of Munich, Garching, Germany

To *invent* an airplane is nothing.
To *build* one is something.
But to *fly* is everything.

Otto Lilienthal

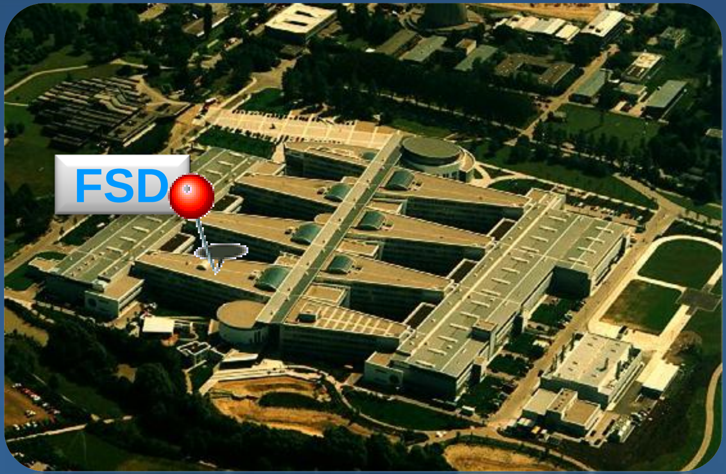
Outline



1. **The Institute of Flight System Dynamics**
2. **Our Academic Research in Flight Control at FSD**
3. **The Classic View on Flight Control**
4. **Making Visions Fly**

Facts and Figures

- **Institute of Flight System Dynamics**
  - Established October 2007
  - Former *Institute of Flight Mechanics and Flight Control*
- **Professors**
  - Prof. Dr.-Ing. Florian Holzapfel
  - Prof. Dr.-Ing. Dr. h.c. Gottfried Sachs
  - Prof. Dr.-Ing. habil. Otto Wagner
- **Senior Researchers**
  - Dr.-Ing. Matthias Heller – Rudolf Diesel Fellow
  - Dr.-Ing. Dipl.-Math. techn. Johann Dambeck
- **Researchers**
  - 37 scientific employees / PhD students including five foreign researchers
  - Eight external PhD students
  - Goal 2012: 45+ employees



Homepage: www.fsd.mw.tum.de
Address: Boltzmannstraße 15
D - 85748 Garching
E-Mail: florian.holzapfel@tum.de
Telephone: +49 89 289-16081
Fax: +49 89 289-16058

Teaching

Lectures

- Flight System Dynamics I & II
- Flight Control I & II
- Flight Guidance
- Navigation and Data Fusion
- Flight Dynamics Challenges of Highly Augmented Configurations
- Nonlinear Adaptive Flight Control
- Development of Flight Control Systems
- Aircraft Trajectory Optimization
- *Aircraft Parameter Estimation (2013)*

Practical Courses

- Flight Guidance
- Flight Testing
- Fundamentals of Practical Flight
- *FCS Development (2013)*

Infrastructure

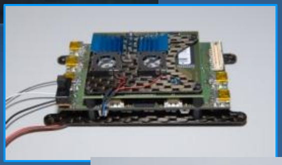
- Research Flight Simulator
- Student Flight Simulator
- Certifiable Flight Simulator
  FTD Level 5+ / Level 6
- Representative Flight Control Hardware (Iron Bird & Actuators)
- Low-Cost Sensors
  (GPS, Inertial, Pressure, Loggers, …)
- Three Quadrocopters fully equipped, Sensors, Controllers, Data Links,…
- Three different Fixed Wing UAVs
- Fly-By-Wire GA Iron Bird
- Motor Glider Grob G-109B
- EMA Actuator and Testbed,
  AFDX Data Bus, Interface …













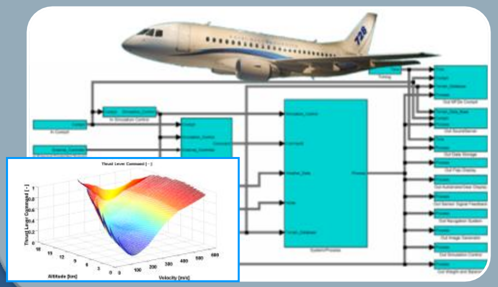


Development / Procurement

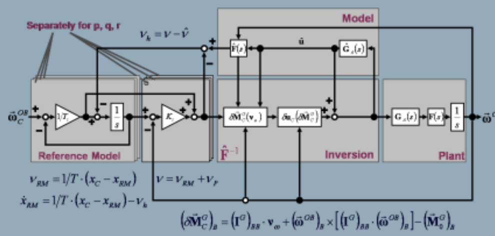
- Twin-Engine Flying Testbed DA42MNG
- Certifiable Avionics Platform
- Additional Sensors:
  Laser, Radar, Scanners, Airdata …

Main Research Areas

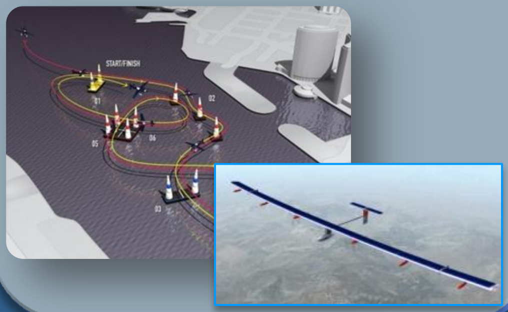
Modeling, Simulation & Parameter Estimation



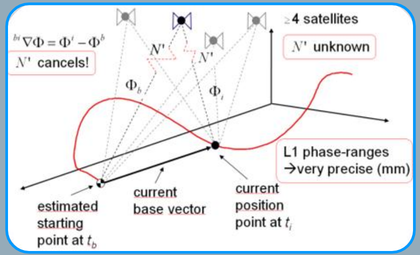
Flight Control & Flight Guidance



Trajectory Optimization

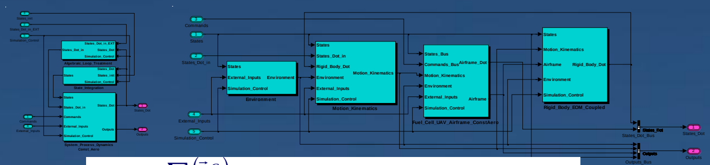


Sensors, Data Fusion & Navigation



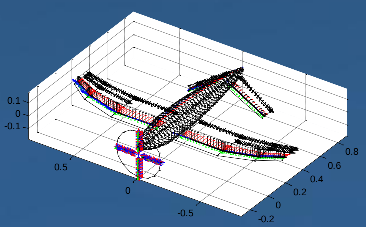
Modeling, Simulation and Parameter Estimation

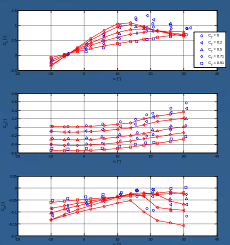
- Structural Model ⇒ high fidelity simulation models



$$\left(\dot{\vec{\mathbf{V}}}_K^G\right)_B^{EB} = \frac{\sum\left(\vec{\mathbf{F}}^G\right)_B}{m} - \left[\mathbf{M}_{BO}\cdot\left(\vec{\boldsymbol{\omega}}_K^{EO}\right)_0 + \left(\vec{\boldsymbol{\omega}}_K^{OB}\right)_B\right]\times\left(\vec{\mathbf{V}}_K^G\right)_B^E - \mathbf{M}_{BO}\cdot\left\{2\cdot\left(\vec{\boldsymbol{\omega}}_K^{IE}\right)_0\times\left(\vec{\mathbf{V}}_K^G\right)_0^E + \left(\vec{\boldsymbol{\omega}}_K^{IE}\right)_0\times\left[\left(\vec{\boldsymbol{\omega}}_K^{IE}\right)_0\times\left(\vec{\mathbf{r}}^G\right)_0\right]\right\}$$

- Initial Parameter / Data Gathering

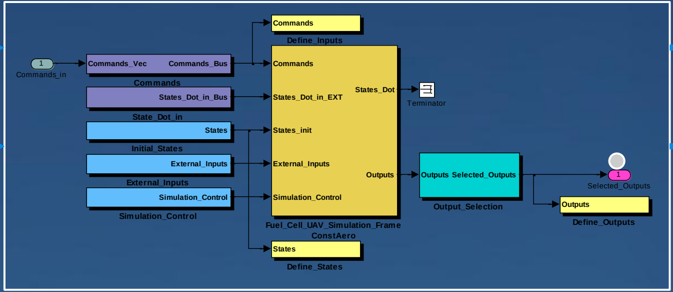




- Simulation
- Trim and Performance Assessment
- Linear System Analysis
- Flight Testing
- Parameter Estimation

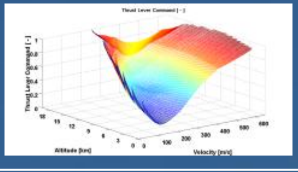
Simulation

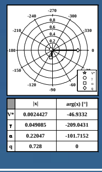
Principle: one model for all applications!

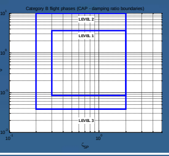


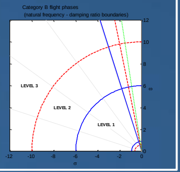
System Analysis

Trim and Performance Assessment → **Linear System Analysis Stability & Control**









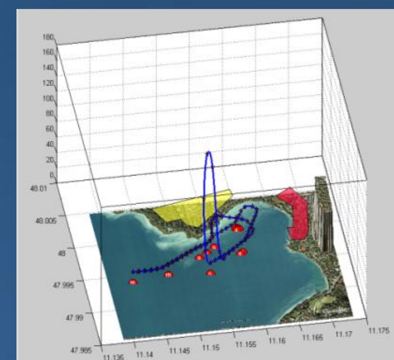
A priori information

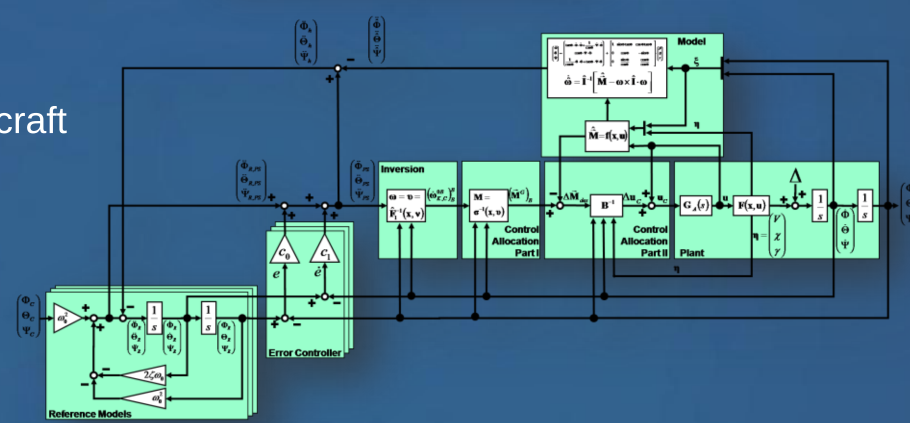
Flight Testing

Parameter Estimation

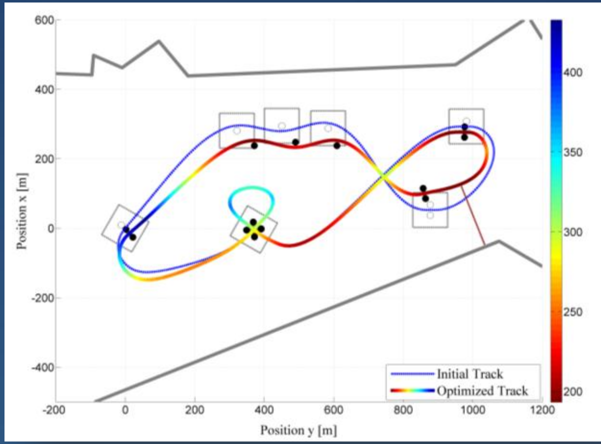
Flight Control & Flight Guidance

- High Level Objectives:
  - Development of control algorithms for real flying systems (manned and unmanned)
  - Application of modern control theory to flying systems
  - Fault tolerant flight control systems
  - Certifiable control systems with guaranteed stability, robustness and performance characteristics
  - Excellent handling qualities and intuitive flying of manned aircraft
  - Increased safety for manned and unmanned aircraft





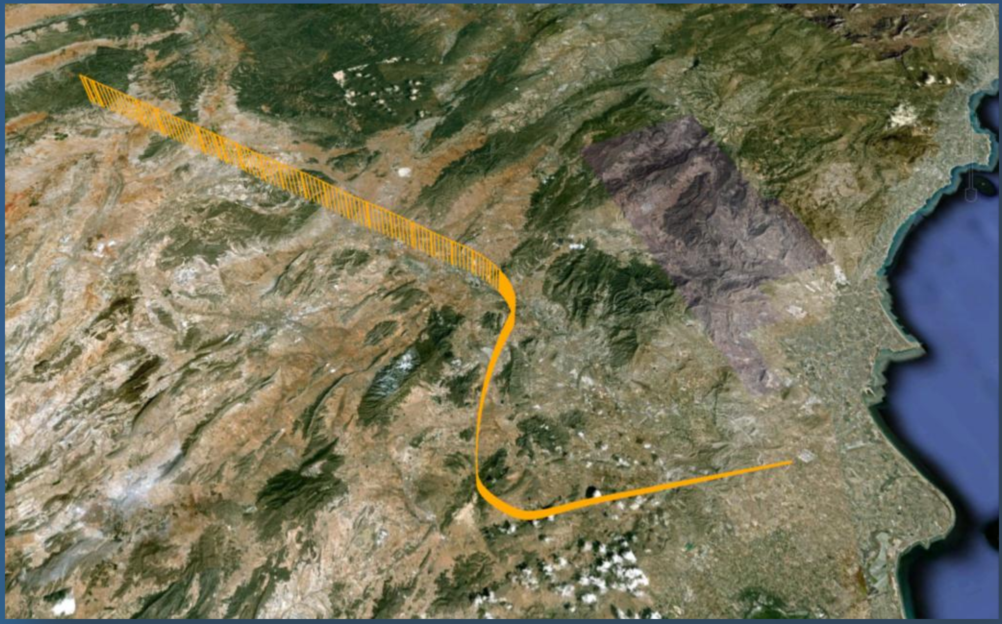
Trajectory Optimization



Mayer Cost Function

Minimizes/ maximizes properties at the beginning or at the end of the trajectory, includes limits for the whole trajectory:

- Flight time
- Fuel consumption
- Maximum range
- Maximum load factors
- Endurance
- Energy at the end of the trajectory:
  - Kinetic/ potential energy
  - Energy stored in fuel cells/ batteries



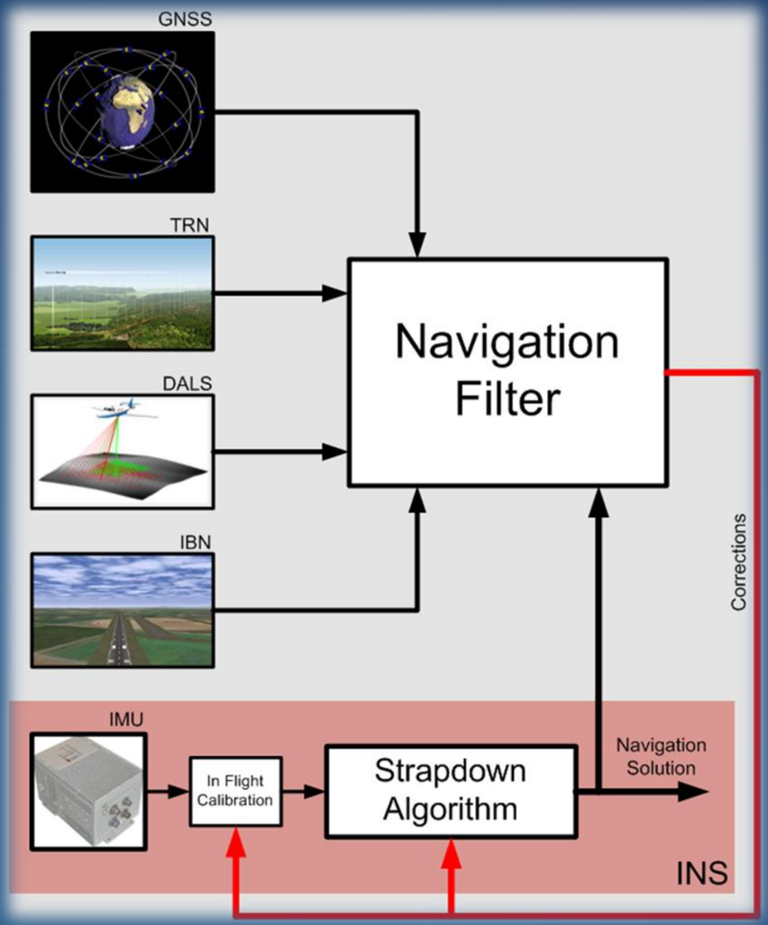
Lagrange Cost Function

Integral cost function,
accumulation over the trajectory

- Emissions
- Noise
- Threats
- Re-entry heating
- Control rates/ actuation activity
- Structural stress/ fatigue

Navigation & Data Fusion

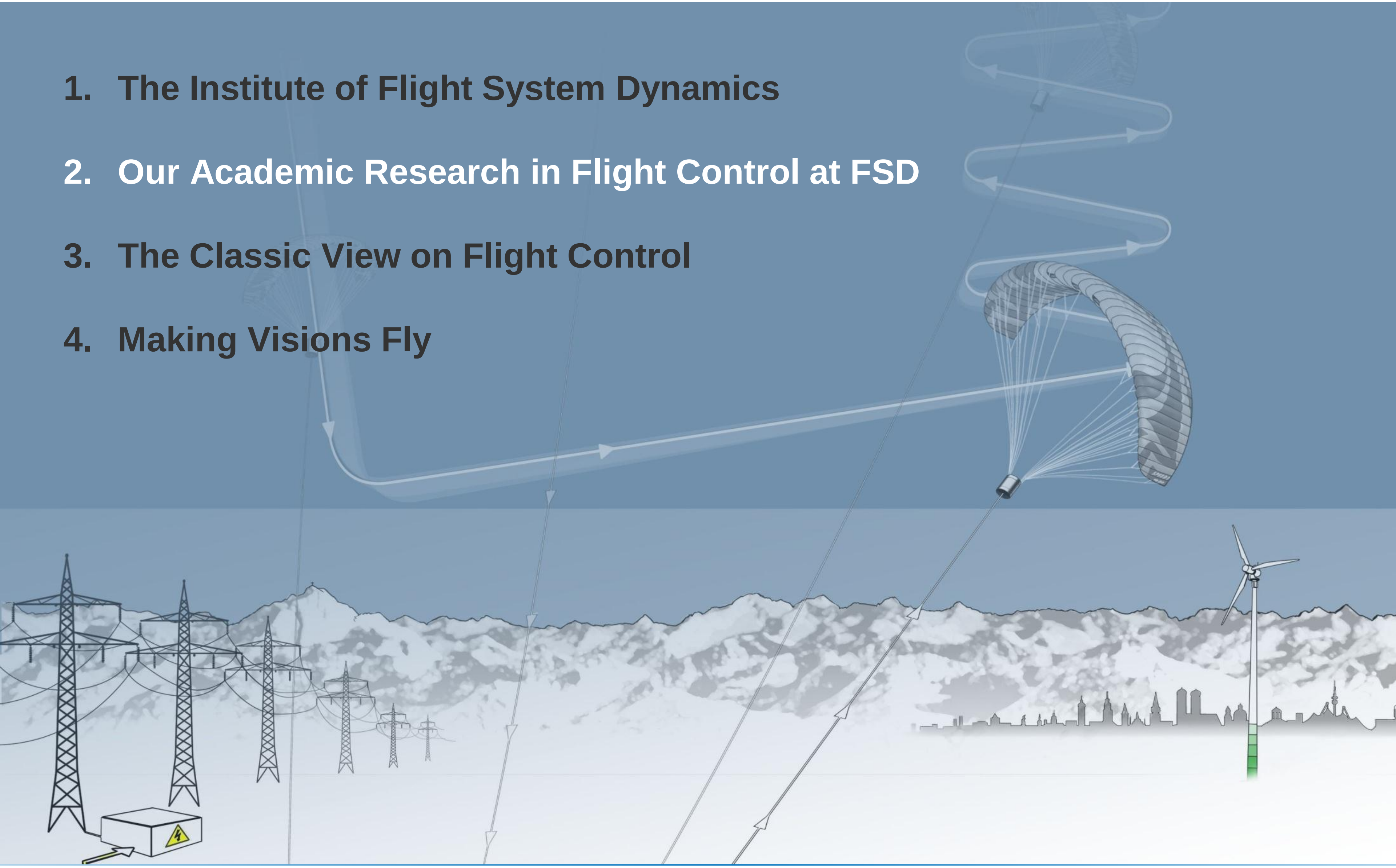
- High-performance algorithms for (low-cost) navigation sensors
- Research on modern sensor data fusion concepts
- Navigation system performance and integrity monitoring
- Analysis of modern navigation techniques:
  - Imaged-based navigation (IBN) (indoor applications, Vision Enhanced Autoland System)
  - Dual Airborne Laser Scanner (DALS)
  - Terrain Reference Navigation (TRN)
- Application of dynamic models and methods from system identification and integrated navigation
- Simulation-Toolbox for integrated nav. systems (Inertial navigation systems, GNSS simulation, data fusion filters, sensor error propagation analysis, …)
- Demonstration of navigation algorithms on UAVs



Video Rakete

Outline

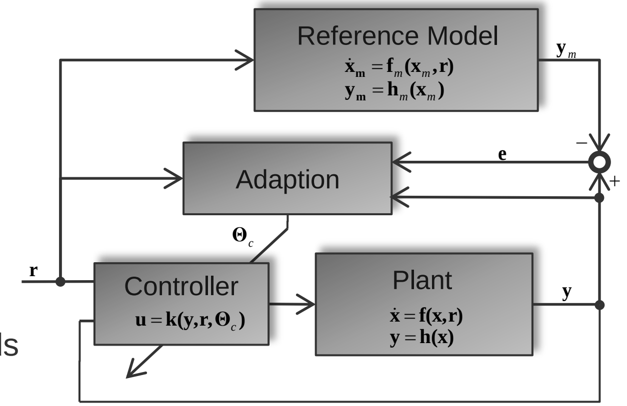
1. The Institute of Flight System Dynamics
2. Our Academic Research in Flight Control at FSD
3. The Classic View on Flight Control
4. Making Visions Fly



Aspects dedicated to Adaptive Control

- Controlling deterministic time continuous systems with parametric and dynamic uncertainties
- Online parameter estimation based on measured error signals to maintain consistent performance in the presence of uncertainties and failure
- Adaptive control techniques can be used to augment existing, robust controllers in order to optimize performance
- Adaptive control can maintain performance in adverse conditions
- Has the potential for saving time and money
  - No exact models needed as in classical control approaches
  - Plant dynamic is assumed to be unknown
  - Uniform performance for all possible unknown dynamics
- In the recent years a coherent theory was developed and adaptive control was used in many practical applications

Nonlinear Adaptive Control

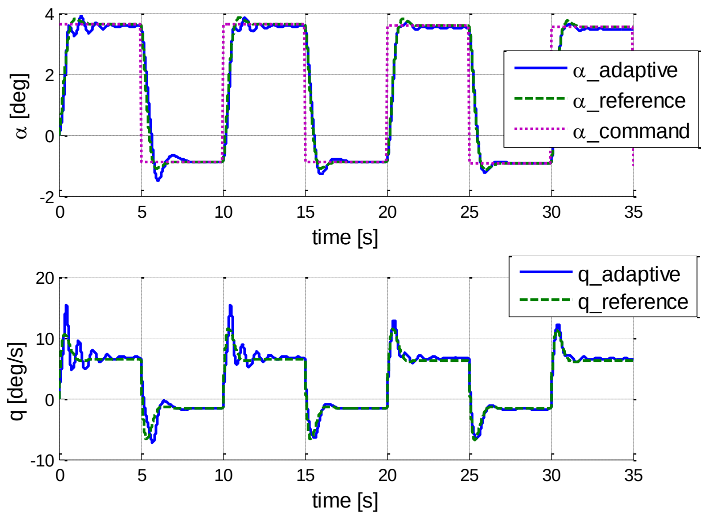


- Control Objectives – "Our Objectives"
  - Autonomous following of highly curved trajectories
  - Full utilization of control power and redundancy (all control surfaces, max. amplitude und max. rate)
  - Dynamic adherence to flight envelope limits (without conservative margins)
  - Control objective conflict resolution: conflicting / unachievable commands
  - High robustness – model, parameter and sensor uncertainties
  - Fault Tolerant, Robust Flight Control
  - Adaptive control – failure, configuration change: "Never-Give-Up-Strategy" (e.g. blocked control surfaces; sensor loss)
  - Fast adaptation to increase survivability and reduce the dependence on model data
  - Certifiable adaptive systems with guaranteed stability, robustness and performance
  - Design of adaptive controllers based on performance and robustness metrics

- Applications in Multiple Projects:
  - NAFC
  - NICE
  - FAT
  - MODUAV
  - ALUSTRA

Nonlinear Adaptive Control

- Nonlinear Dynamic Inversion
- Lyapunov's Direct Method
- Backstepping, Adaptive Backstepping
- Direct MRAC, Indirect MRAC, Composite MRAC
- L1 Control
- Update Laws (Derivative Free, Gradient, Filter, Lyapunov Based)
- Nonlinear Regressors (e.g. Neural Networks)
- Reference Models (linear, nonlinear)
- Robustness Modifications
- Performance and Robustness Metrics



Adaptive Laws:

$$\dot{\boldsymbol{\Theta}}_x = -\boldsymbol{\Gamma}_x \operatorname{sgn}(\boldsymbol{\Lambda})\mathbf{B}_P^T\mathbf{P}\mathbf{e}_c \cdot \mathbf{x}_P^T - \sigma\|\mathbf{e}\|\boldsymbol{\Theta}_x$$

$$\dot{\boldsymbol{\Theta}}_r = -\boldsymbol{\Gamma}_r \operatorname{sgn}(\boldsymbol{\Lambda})\mathbf{B}_P^T\mathbf{P}\mathbf{e}_c \cdot \mathbf{r}^T - \sigma\|\mathbf{e}\|\boldsymbol{\Theta}_r$$

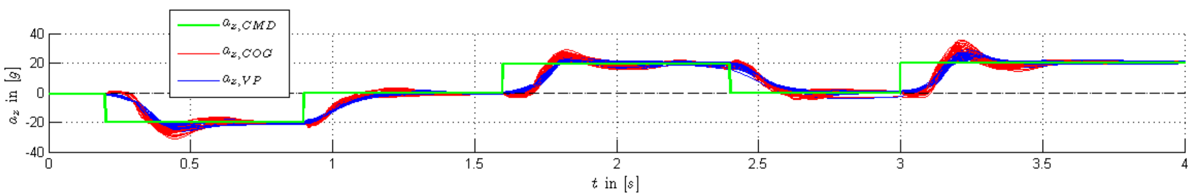
$$\dot{\boldsymbol{\Theta}}_\varphi = -\boldsymbol{\Gamma}_x \operatorname{sgn}(\boldsymbol{\Lambda})\mathbf{B}_P^T\mathbf{P}\mathbf{e}_c \cdot \boldsymbol{\varphi}^T(\mathbf{x}_P) - \sigma\|\mathbf{e}\|\boldsymbol{\Theta}_\varphi$$

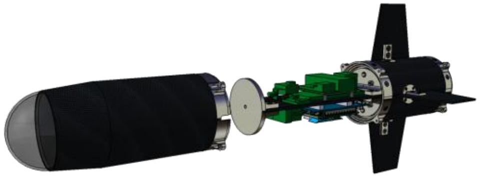
$$\dot{\boldsymbol{\Theta}}_d = -\boldsymbol{\Gamma}_d \operatorname{sgn}(\boldsymbol{\Lambda})\mathbf{B}_P^T\mathbf{P}\mathbf{e}_c - \sigma\|\mathbf{e}\|\boldsymbol{\Theta}_d$$

Nonlinear Adaptive Control for Missile Applications

- Different Missile Types: Tail-Controlled Missile, Canard-Controlled Missile (Missile available), Tail-Controlled Missile using Reaction Jets
- Used Adaptation Strategies: L1-Adaptive Control, Model Reference Adaptive Control, Adaptive Backstepping
- Type of Cooperation: Fundamental Research, Research and Development

- Work share of FSD in several projects:
  - Adaptive flight control based on nonlinear dynamic inversion for missiles featuring a high level of uncertainties and nonlinearities
  - Development and assembly of a reusable low cost missile
  - High fidelity missile simulations combined with flight tests
  - Tailoring an Adaptive Backstepping approach to a tail-controlled missile using Reaction Jets



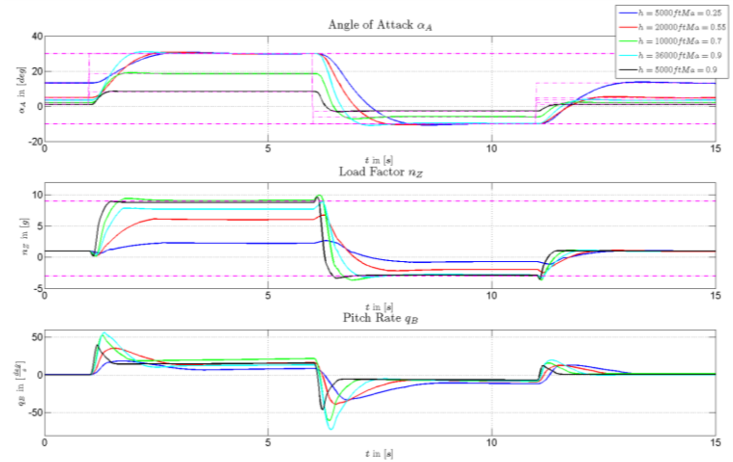


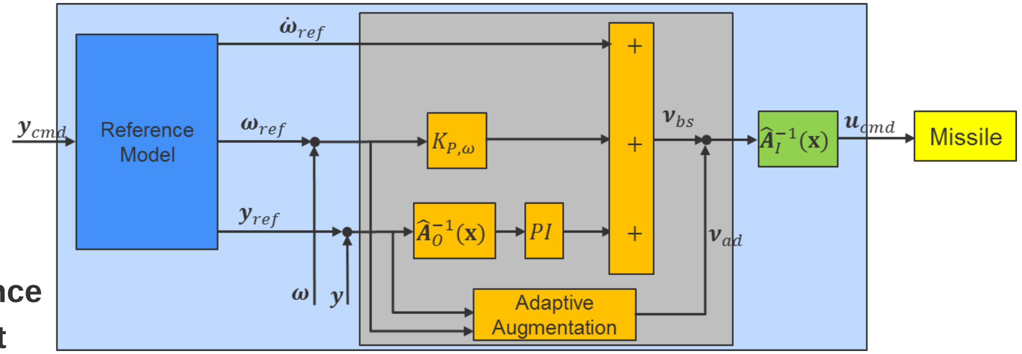
Nonlinear Innovative Control Designs and Evaluations (NICE) – An EDA (European Defense Agency) project

- Derivation and assessment of different baseline inversion strategies with respect to nonlinearities addressed, relative degree, model assumed for inversion (not necessarily the nominal model), model parameterization
- Applications:
  - Generic surface-to-air missile model
  - Combat aircraft model
- Development of a new, physically motivated Reference Model
  - Highly nonlinear
  - One Reference Model outputting all the necessary signals
  - Uses the full physical capabilities of the plant
- Redesign of the Baseline Controller according to the change in the Reference Model

  ⇨ Leads to an almost linear error dynamics, which is perfectly suitable for MRAC
- Adaptive Augmentation of the Baseline Controller
  - Direct MRAC
  - L1/PWC

  ⇨ Physically motivated choice of the learning rates





⇨ **New developments lead to an increase in performance and utilizes the full physical capabilities of the plant**

Nonlinear Adaptive Control for Aircraft Applications

- Type of Cooperation: Fundamental Research, Research and Development

- Basic research on Model Reference Adaptive Control (MRAC)
  - Structure (Direct, Indirect, Combined, $\mathcal{L}_1$, …)
  - Regressor (Linear, Nonlinear, Neural Networks)
  - Update laws and modifications (Lyapunov, Gradient, Filter)
  - Robustness modifications for parameter boundedness
  - Design of reference models (linear, nonlinear, constraints, …)
  - Heging of reference model

Adaptive Laws:

$$\dot{\boldsymbol{\Theta}}_{\mathrm{x}} = -\boldsymbol{\Gamma}_{\mathrm{x}} sgn(\boldsymbol{\Lambda}) \cdot \mathbf{x} \cdot \mathbf{e}_{\mathrm{c}} \mathbf{P} \mathbf{B}_P - \sigma \|\mathbf{e}\| \boldsymbol{\Theta}_{\mathrm{x}}$$

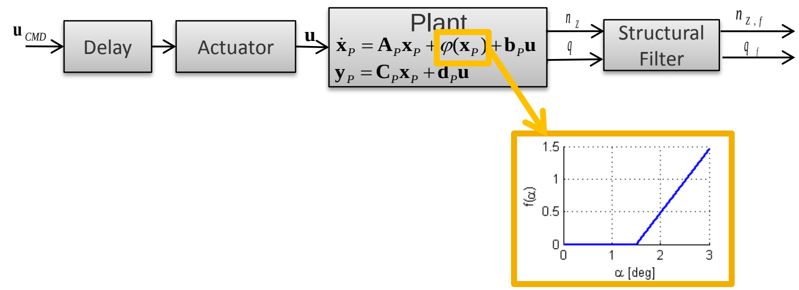
$$\dot{\boldsymbol{\Theta}}_{\mathrm{r}} = -\boldsymbol{\Gamma}_{\mathrm{r}} sgn(\boldsymbol{\Lambda}) \cdot \boldsymbol{r} \cdot \mathbf{e}_{\mathrm{c}} \mathbf{P} \mathbf{B}_P - \sigma \|\mathbf{e}\| \boldsymbol{\Theta}_{\mathrm{x}}$$

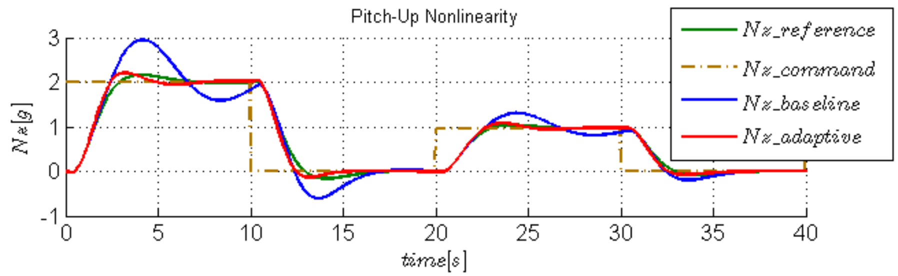
$$\dot{\boldsymbol{\Theta}}_{\varphi} = -\boldsymbol{\Gamma}_{\varphi} sgn(\boldsymbol{\Lambda}) \cdot \boldsymbol{\varphi}(\mathbf{x}_{\mathrm{P}}) \cdot \mathbf{e}_{\mathrm{c}} \mathbf{P} \mathbf{B}_P - \sigma \|\mathbf{e}\| \boldsymbol{\Theta}_{\mathrm{x}}$$

- Application to Use-Cases
  1) Pitch-up nonlinearity:
  2) Nonlinear model of large transport aircraft: Elimination of gain scheduling parameters

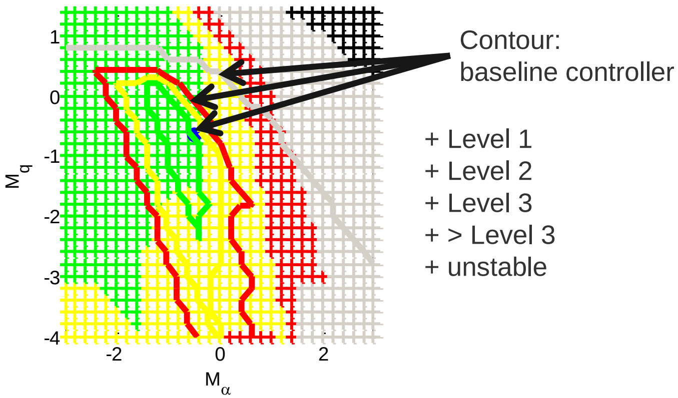
Nonlinear Adaptive Control for Aircraft Applications

1) Pitch-up nonlinearity:
   - Short period model
     - With nonlinear pitch-up
     - Including sensor and actuator model
   - To compensate for the nonlinearity different adaptive methods are applied and compared
     - ⇨ Performance Metrics
     - ⇨ Robustness Metrics (Time delay margin)



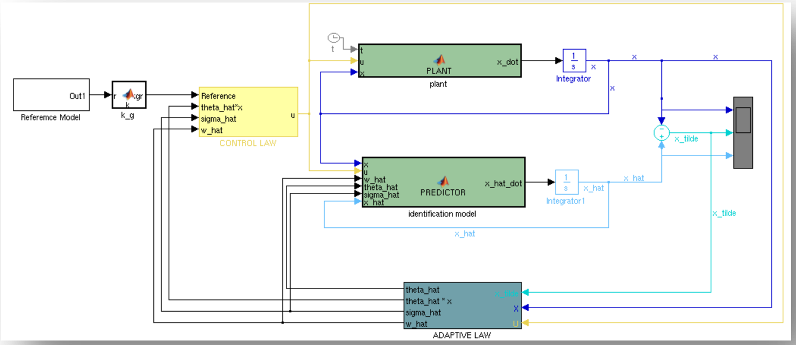


2) Nonlinear model of large transport aircraft:
   - Airbus Simulation Model
     - ⇨ 6DoF model
     - ⇨ Including sensor and actuator model
   - Problem: Loss of scheduling parameters (V_{CAS})
   - Definition of Requirements
     - ⇨ Handling requirements
     - ⇨ Performance Metrics
     - ⇨ Robustness Metrics (Time delay margin)
   - Augmentation of the baseline controller with an adaptive controller
     - ⇨ MRAC
     - ⇨ $\mathcal{L}_1$ piecewise constant
   - Application of Kalman Filter to estimate the scheduling parameters
   - Investigation of performance and robustness
   - in the presence of uncertainties



Nonlinear Adaptive Control for Helicopter Applications

- Project Description:
    - Closed loop real-time simulation with the nonlinear, adaptive L1 control structure
    - Development of a certification strategy for the L1 controller
    - Evaluation in regard to existing baseline controller



Structure:

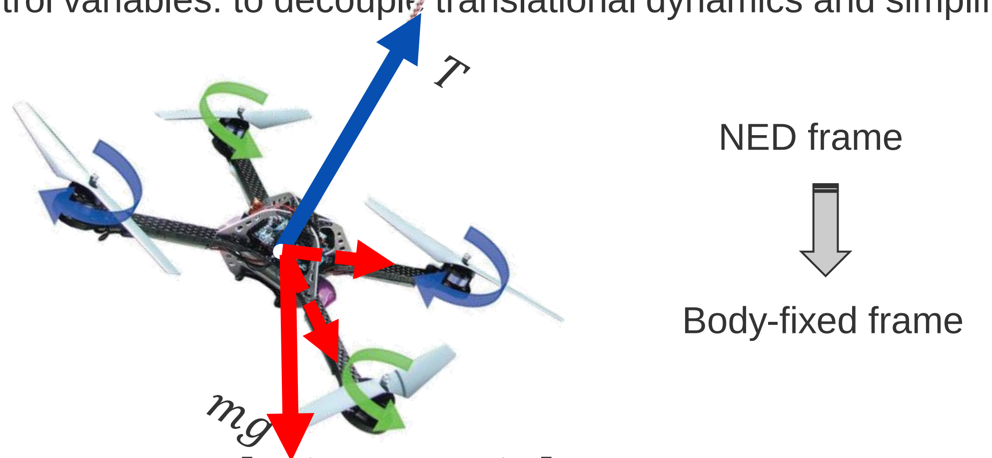
- For the helicopter a linear baseline controller exists
- In nominal condition, the baseline controller remains the active controller
- In adverse conditions, the adaptive L1 controller augments the linear one

Tasks:

- Implementation of an optional L1 controller by incorporating but not touching the existing baseline controller
- Development of a valid certification strategy
- Comparison of the augmented system with the controller designed for nominal conditions

Nonlinear Control for Quadrocopters

- Design Objectives: high bandwidth, robustness and accuracy
  - Able to utilize the accelerometer measurements in the control feedback
    - accelerometer xy axis: external distrubance and aerodynamic forces
- New Mathematical model for control design
  - Novel control variables: to decouple translational dynamics and simplify computations

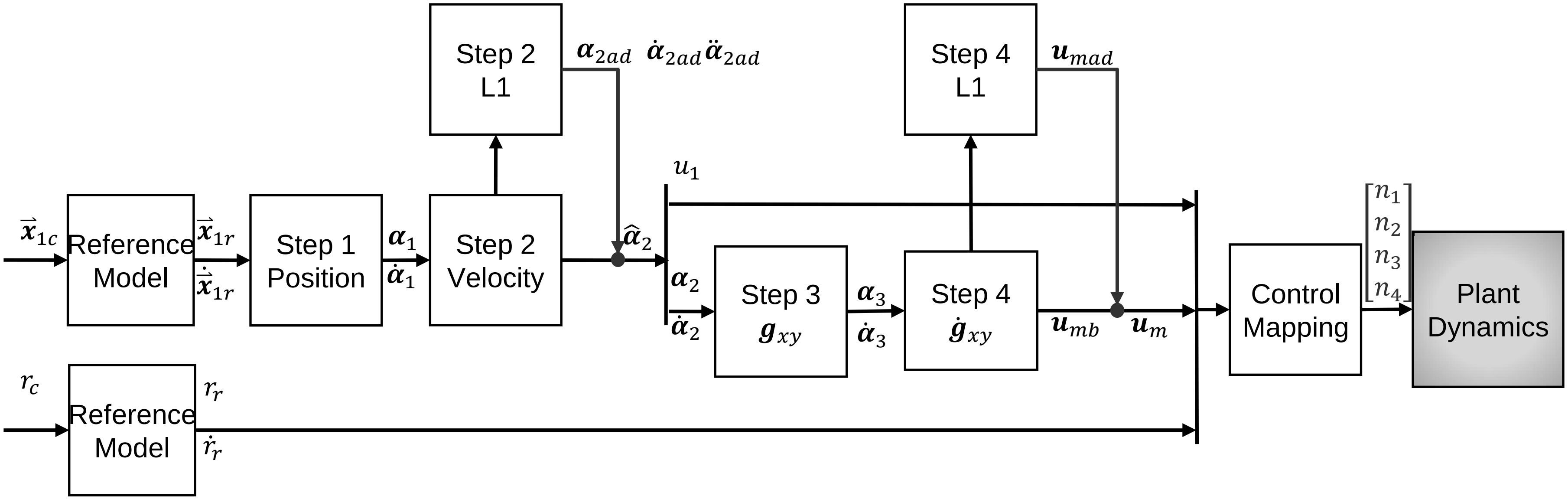


$$\vec{\boldsymbol{g}}_B = \boldsymbol{M}_{BW} \cdot \vec{\boldsymbol{g}}_W = g \cdot \begin{bmatrix} 2(q_1 q_3 - q_0 q_2) \\ 2(q_2 q_3 + q_0 q_1) \\ q_0^2 - q_1^2 - q_2^2 + q_3^2 \end{bmatrix} = g \cdot \begin{bmatrix} sin\Theta cos\Phi \\ -sin\Phi \\ cos\Theta cos\Phi \end{bmatrix} = \begin{bmatrix} g_x \\ g_y \\ g_z \end{bmatrix}_B$$

  - Translational dynamic equation (W: world frame)

$$\left(\dot{\vec{\boldsymbol{v}}}_k^G\right)_W^{WW} = \boldsymbol{M}_{WB} \left(\begin{bmatrix} f_x \\ f_y \\ \underbrace{f_z + T/m}_{\approx 0} - T/m \end{bmatrix}_B + \begin{bmatrix} g_x \\ g_y \\ g_z \end{bmatrix}_B \right) = \boldsymbol{M}_{WB} \left(\underbrace{\begin{bmatrix} f_x \\ f_y \\ g_z \end{bmatrix}_B}_{Meas} + \underbrace{\begin{bmatrix} g_x \\ g_y \\ -T/m \end{bmatrix}_B}_{decoupled\ controls} \right)$$

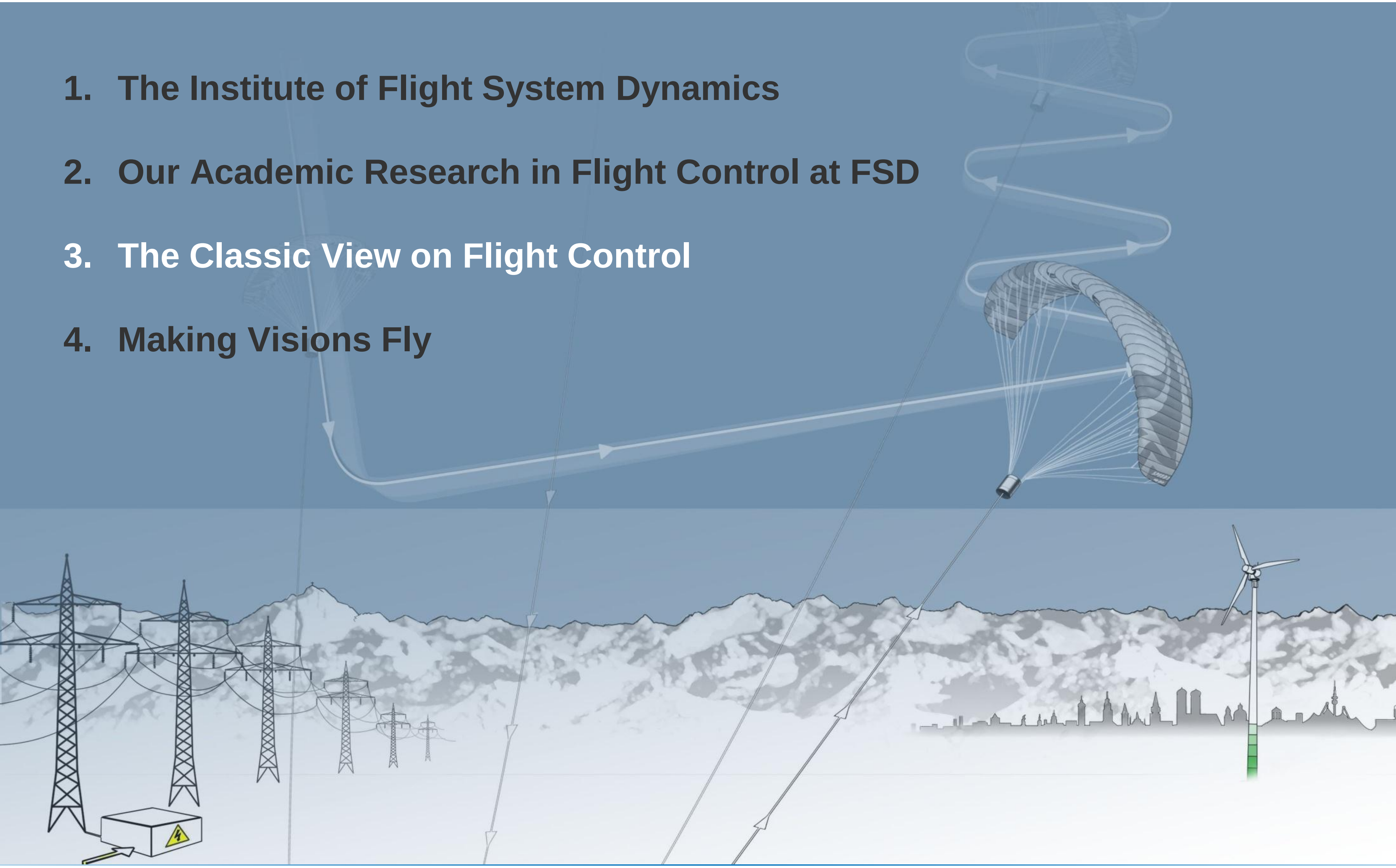
- Novel baseline position control structure designs using D.I./backstepping
  - Position loop of Relative Degree (RD) 2 + gxy loop of RD2
  - Position loop of RD3 + Rate loop of RD1 structure
- Augumented L1 adaptive control based on the error model to account for model uncertainties
- Example: L1 Backstepping design structure



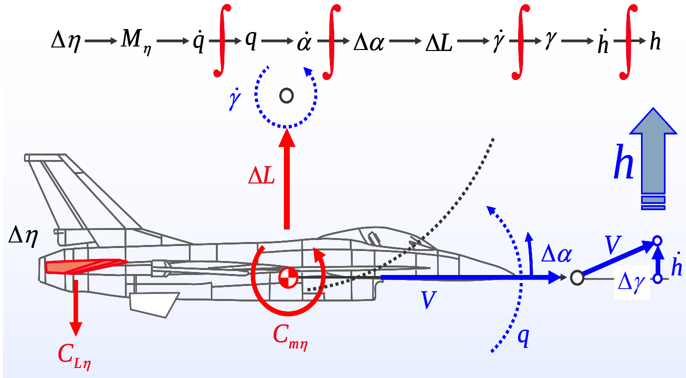
Video: Quadrocopter

Outline

1. The Institute of Flight System Dynamics
2. Our Academic Research in Flight Control at FSD
3. **The Classic View on Flight Control**
4. Making Visions Fly



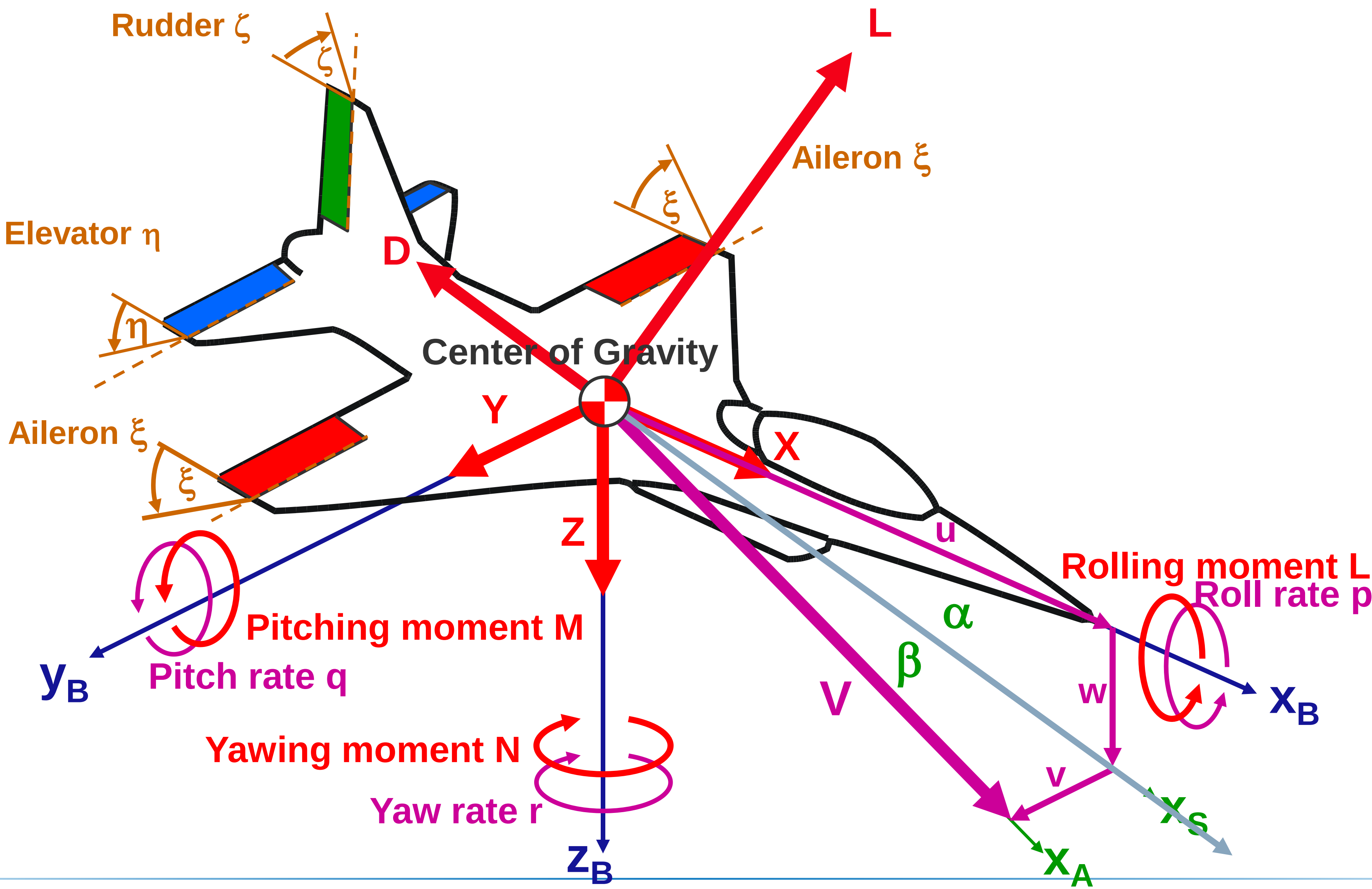
- Unique Plant to be Controlled: The Aircraft
  - Profoundly nonlinear plant
  - Large Envelope concerning flight conditions and configurations
  - Strong coupling of variables to be controlled
  - Unavailable or complex measurements
  - Large, manifold & changing model uncertainties
  - Highly dynamic external disturbances
  - Consequences of a Failure
- Novel Systems (UAV, HAWE, …)
  - Unconventional configurations/shapes
  - Novel operational concepts & strategies
  - Increased Need for Automation / Autonomy
  - ⇨ New requirements and challenges



Source: Makani

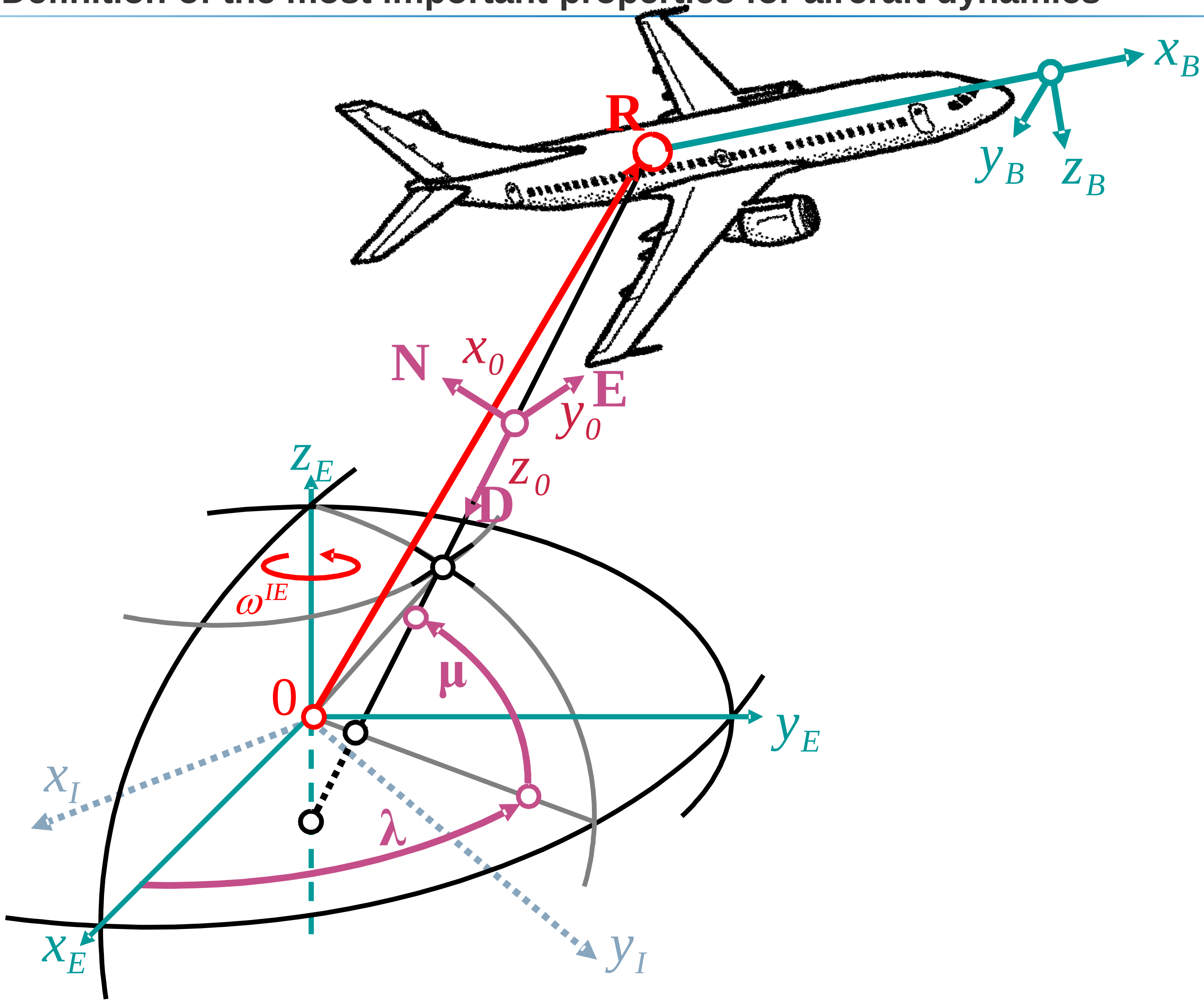
The Classic View on Flight Control

Definition of the most important properties for aircraft dynamics

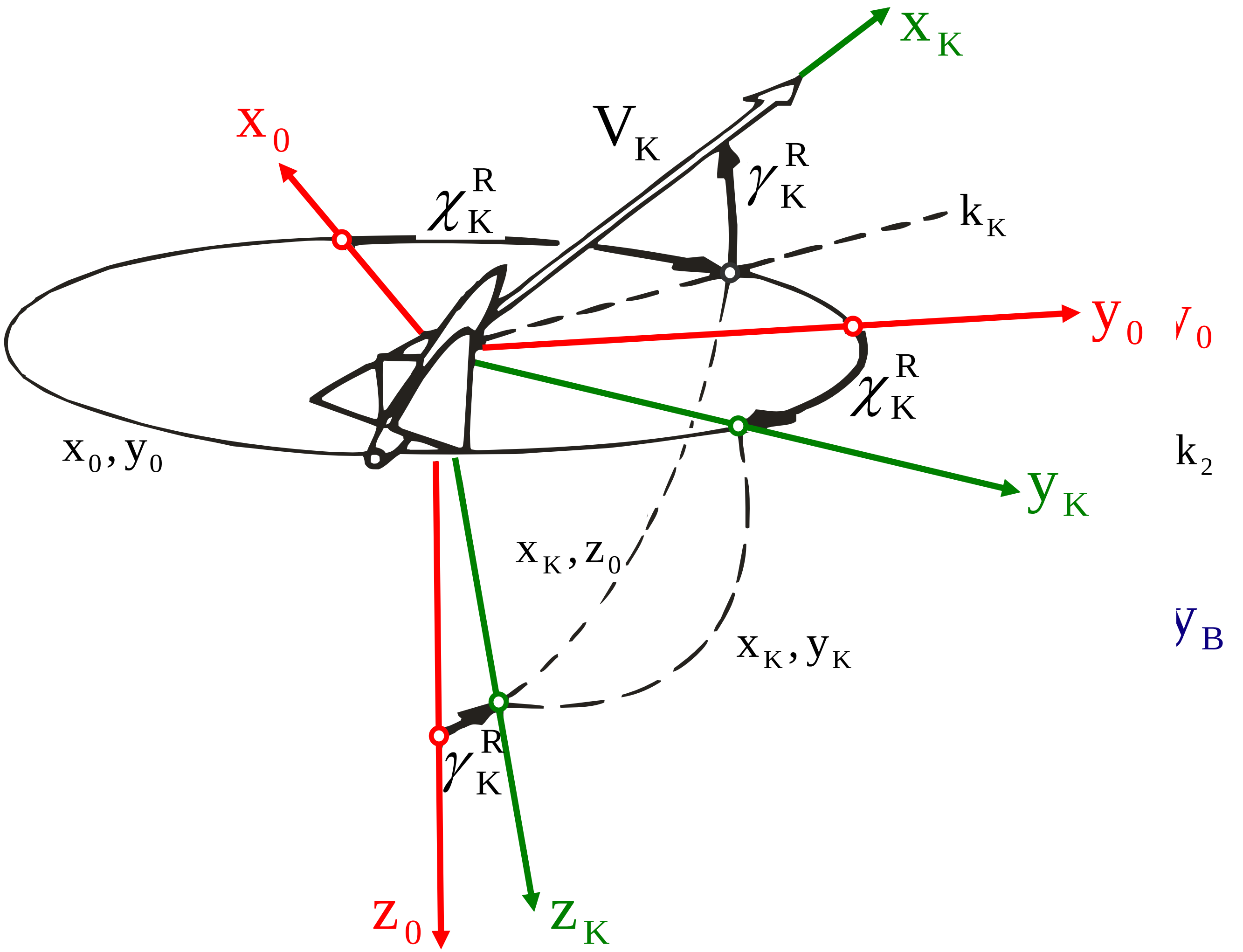


The Classic View on Flight Control

Definition of the most important properties for aircraft dynamics

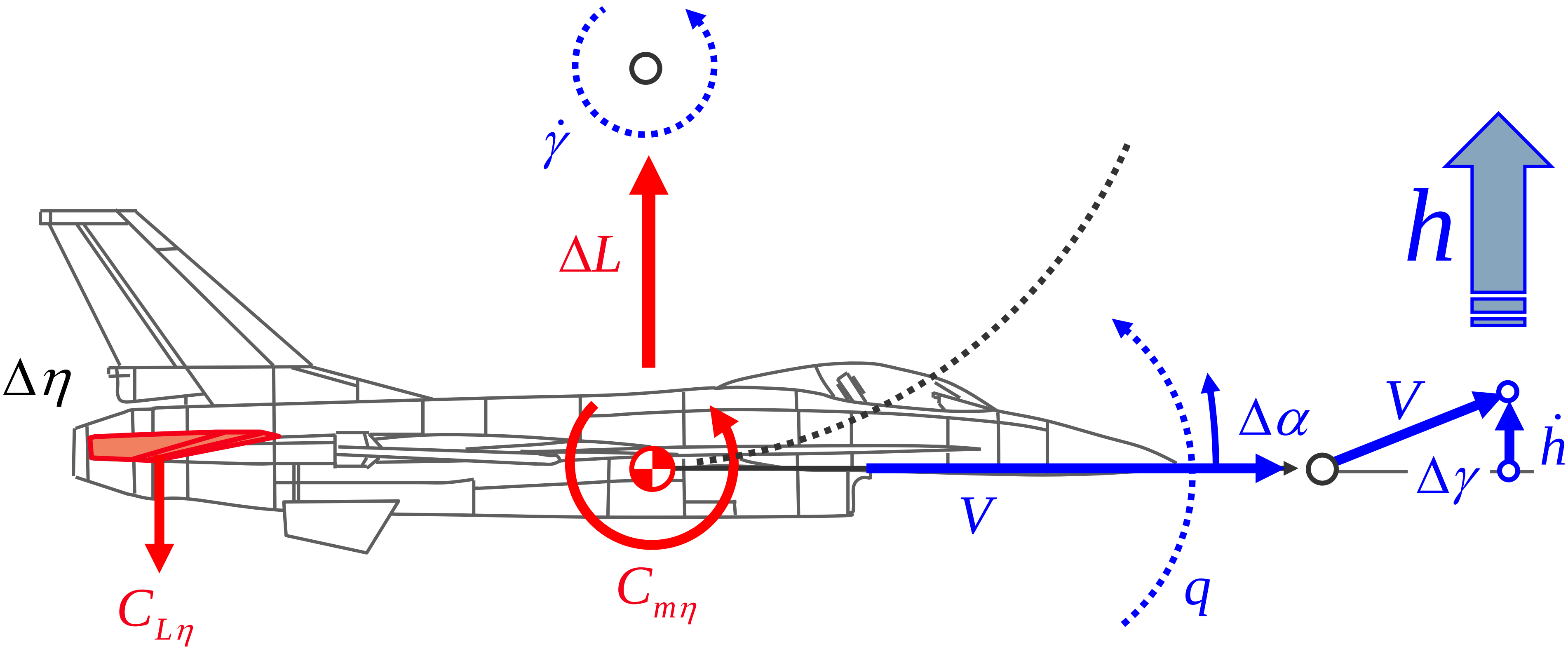


Direction of Flight / *Spatial Attitude*



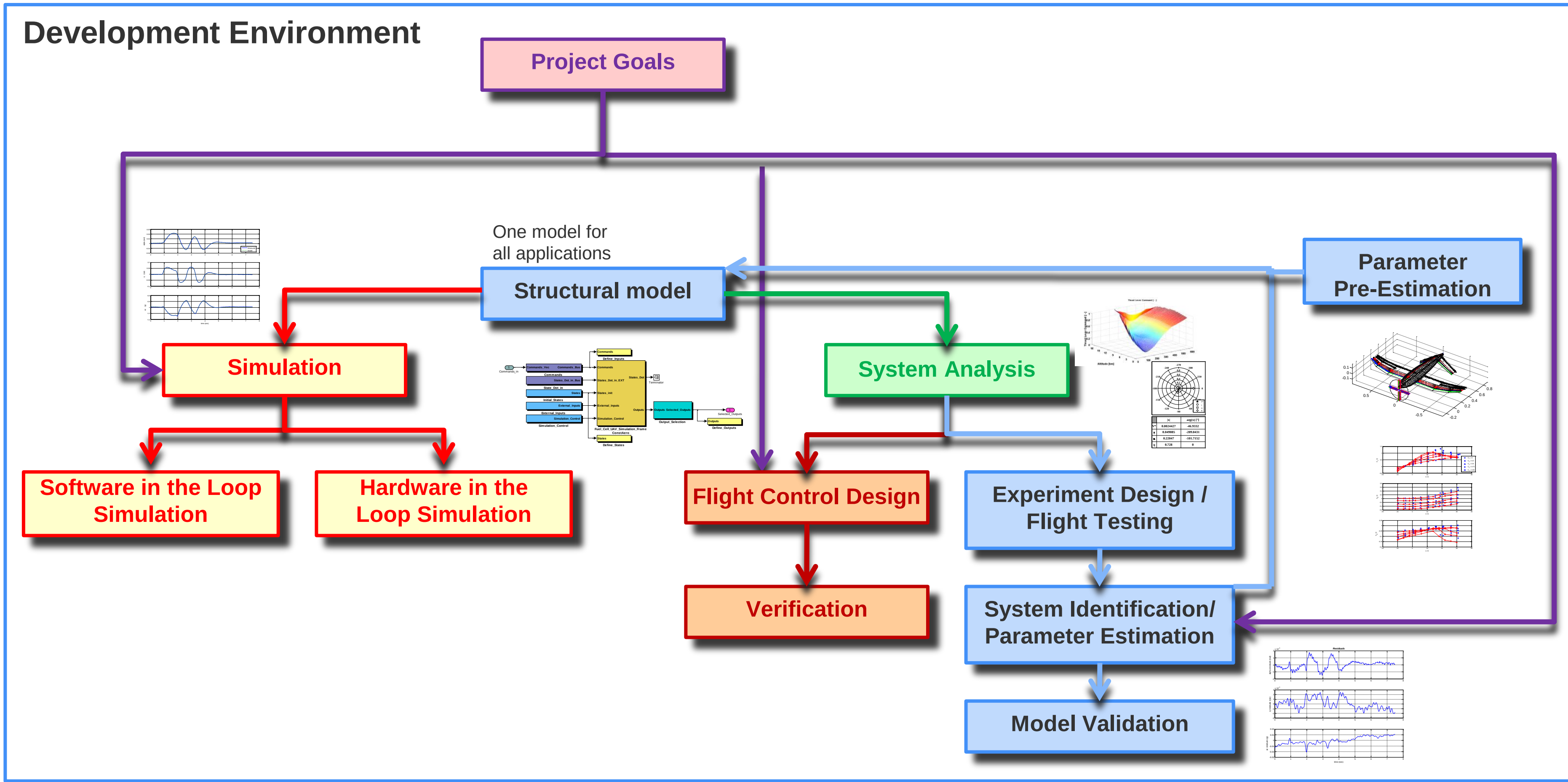
Example: causal chain from elevator deflection η to change in altitude h

$$\Delta\eta \longrightarrow M_\eta \longrightarrow \dot{q} \int q \longrightarrow \dot{\alpha} \int \Delta\alpha \longrightarrow \Delta L \longrightarrow \dot{\gamma} \int \gamma \longrightarrow \dot{h} \int h$$



The Classic View on Flight Control

Model-based development



The Classic View on Flight Control
The simulation model

Simulation Model:

Mathematical representation of aircraft dynamics based on ordinary differential equations.

State Space Model:

The aircraft motion can be described by the concept of a state space model.
It describes the temporal change (first order time derivative) of the state variables as a function of the current state variables and the current inputs (controls and disturbances).
The state vector consist of the minimum number of variables (states) required to completely and unambiguously describe the actual situation of the system.

In symbolic expressions:

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u})$$

explicit model
(ODE)

$$\mathbf{f}(\mathbf{x}, \dot{\mathbf{x}}, \mathbf{u}) = \mathbf{0}$$

Implicit model
(DAE)

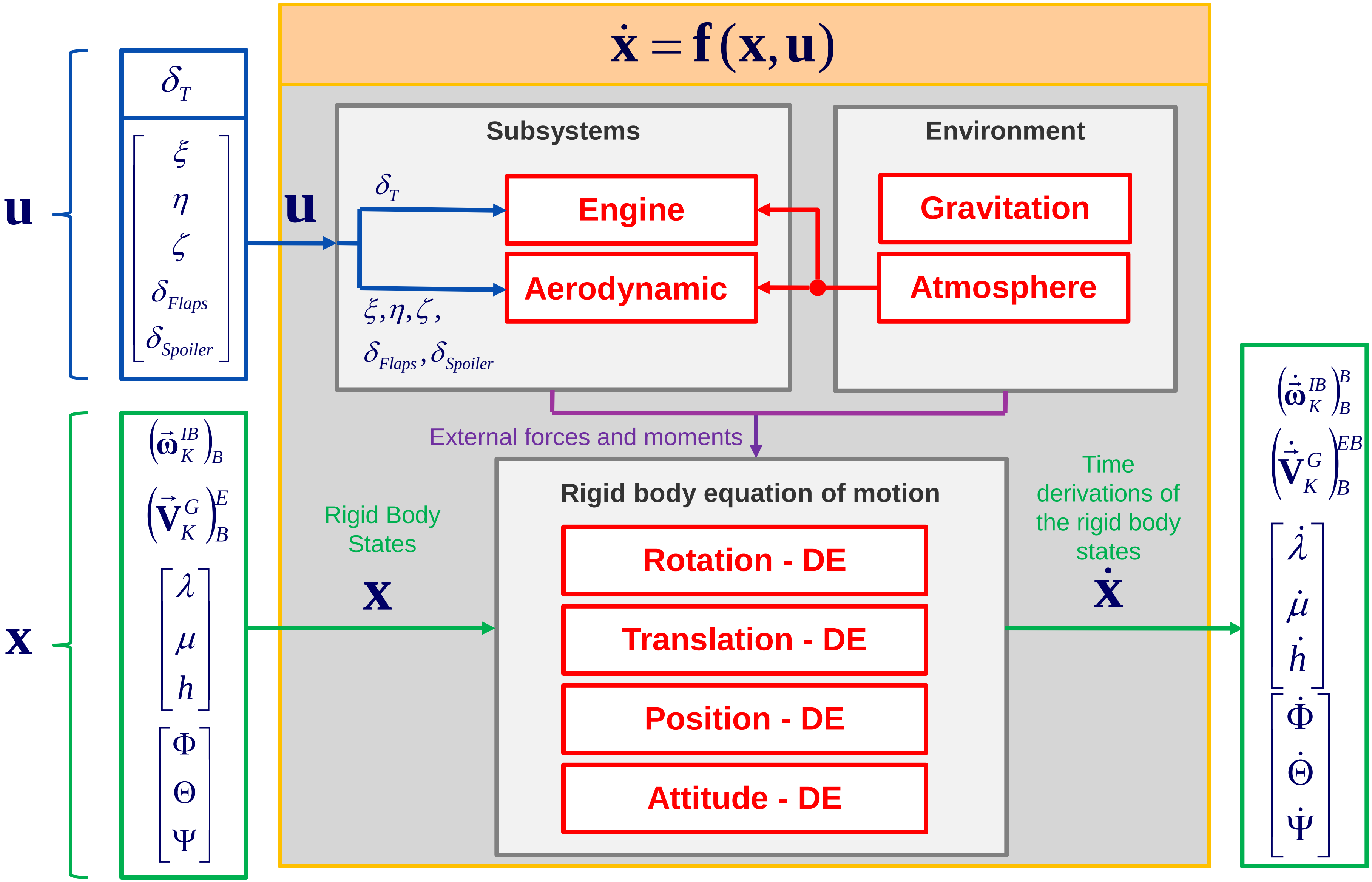
Example: rigid body states and control inputs

$$\mathbf{x} = \begin{bmatrix} \left(\vec{\mathbf{V}}_K^G\right)_B^E \\ \left(\vec{\boldsymbol{\omega}}_K^{IB}\right)_B \\ \begin{bmatrix} \Phi \\ \Theta \\ \Psi \end{bmatrix} \\ \begin{bmatrix} \lambda \\ \mu \\ h \end{bmatrix} \end{bmatrix} \quad \begin{matrix} \text{Translation} \\ \text{Rotation} \\ \text{Attitude} \\ \text{Position} \end{matrix}$$

$$\mathbf{u} = \begin{bmatrix} \delta_T \\ \begin{bmatrix} \xi \\ \eta \\ \zeta \\ \delta_{Flaps} \\ \delta_{Spoiler} \end{bmatrix} \end{bmatrix} \quad \begin{matrix} \text{Propulsion} \\ \text{Aerodynamic Control Surfaces} \end{matrix}$$

The Classic View on Flight Control

The rigid body simulation model



The Classic View on Flight Control

The rigid body simulation model

Force equations, no wind, flat and non-rotating earth

$$\dot{V} = -\frac{D}{m} + \frac{\left[\left(X_P^G\right)_B \cos\alpha\cos\beta + \left(Y_P^G\right)_B \sin\beta + \left(Z_P^G\right)_B \sin\alpha\cos\beta\right]}{m} - g\sin\gamma$$

$$\dot{\alpha} = \frac{-L}{mV\cos\beta} + \frac{-\left(X_P^G\right)_B \sin\alpha + \left(Z_P^G\right)_B \cos\alpha}{mV\cos\beta} + \frac{g}{V}\cdot\frac{\cos\mu\cos\gamma}{\cos\beta} + \left[q - \tan\beta\left(p\cos\alpha + r\sin\alpha\right)\right]$$

$$\dot{\beta} = \frac{Q}{mV} + \frac{\left[-\left(X_P^G\right)_B \cos\alpha\sin\beta + \left(Y_P^G\right)_B \cos\beta - \left(Z_P^G\right)_B \sin\alpha\sin\beta\right]}{mV} + \frac{g}{V}\cdot\cos\gamma\sin\mu + \left(-r\cos\alpha + p\sin\alpha\right)$$

Moment equations, no wind, flat and non-rotating earth

$$\dot{p} = \frac{1}{\Delta}\cdot\left[I_{zz}\cdot\left(L_A^G\right)_B + I_{xz}\cdot\left(N_A^G\right)_B\right] + \frac{1}{\Delta}\cdot\left[I_{zz}\cdot\left(L_P^G\right)_B + I_{xz}\cdot\left(N_P^G\right)_B\right] + \frac{1}{\Delta}\cdot\left[I_{xz}\cdot\left(I_{xx} - I_{yy} + I_{zz}\right)\cdot p\cdot q - \left(I_{zz}^2 - I_{zz}\cdot I_{yy} + I_{xz}^2\right)\cdot q\cdot r\right] \qquad \Delta = \left(I_{xx}I_{zz} - I_{xz}^2\right)$$

$$\dot{q} = \frac{1}{I_{yy}}\cdot\left(M_A^G\right)_B + \frac{1}{I_{yy}}\cdot\left(M_P^G\right)_B + \frac{1}{I_{yy}}\cdot\left[I_{xz}\cdot\left(r^2 - p^2\right) - \left(I_{xx} - I_{zz}\right)\cdot p\cdot r\right]$$

$$\dot{r} = \frac{1}{\Delta}\cdot\left[I_{xz}\cdot\left(L_A^G\right)_B + I_{xx}\cdot\left(N_A^G\right)_B\right] + \frac{1}{\Delta}\cdot\left[I_{xz}\cdot\left(L_P^G\right)_B + I_{xx}\cdot\left(N_P^G\right)_B\right] + \frac{1}{\Delta}\cdot\left[\left(I_{xz}^2 - I_{xx}\cdot I_{yy} + I_{xx}^2\right)\cdot p\cdot q - I_{xz}\cdot\left(I_{xx} - I_{yy} + I_{zz}\right)\cdot q\cdot r\right]$$

Attitude propagation, Euler Angles

$$\begin{pmatrix}\dot{\Phi}\\ \dot{\Theta}\\ \dot{\Psi}\end{pmatrix} = \begin{pmatrix}1 & \sin\Phi\tan\Theta & \cos\Phi\tan\Theta\\ 0 & \cos\Phi & -\sin\Phi\\ 0 & \frac{\sin\Phi}{\cos\Theta} & \frac{\cos\Phi}{\cos\Theta}\end{pmatrix}_B \cdot \begin{pmatrix}p\\ q\\ r\end{pmatrix}$$

Position propagation WGS-84

$$\begin{pmatrix}\dot{\lambda}\\ \dot{\mu}\\ \dot{h}\end{pmatrix}_0^E = \begin{pmatrix}\frac{v_K^G}{\left(N_\mu + h\right)\cos\mu}\\ \frac{u_K^G}{M_\mu + h}\\ -w_K^G\end{pmatrix}_0^E$$

$$M_\mu = a\frac{1-e^2}{\left(1-e^2\sin^2\mu\right)^{3/2}} = N_\mu\cdot\frac{1-e^2}{1-e^2\sin^2\mu}$$

$$N_\mu = \frac{a}{\sqrt{1-e^2\sin^2\mu}}$$

Modeling accuracy:

Depending on the purpose of the model, suitable assumptions must be made concerning:

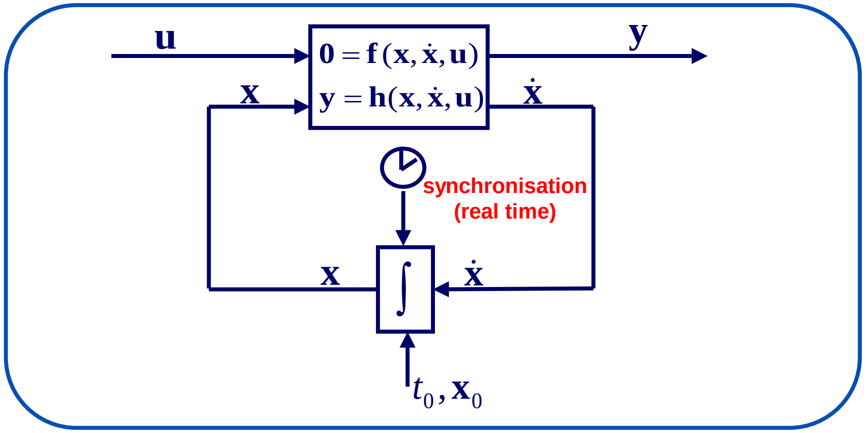
- *Scope (rigid body only, dynamic subsystems,…)*
- *Fidelity (Earth / gravity / atmosphere model,…)*
- *Data fidelity (aerodynamics, propulsion, …)*

The Classic View on Flight Control

Utilization of simulation models in a classical sense

Nonlinear simulation models:

- *Time domain simulation*
- *Single point execution (trim, optimization,…)*
- *Basis for numerical linearization*
- *Real-time or batch*
- *Piloted, MIL, SIL, HIL,PIL*
- *Final clearing stage before real flight closest to reality*



Linear state space models:

- *Stability and control analysis*
- *Eigenvalues and eigenvectors*
- *Transfer functions*
- *Classic controller gain design*
- *Classic stability margins*

$$\begin{bmatrix} \dot{r} \\ \dot{\beta} \\ \dot{p} \\ \dot{\Phi} \end{bmatrix} = \begin{bmatrix} -0.71 & 6.3 & -0.2 & 0 \\ -1 & -0.23 & 0 & 0.15 \\ 1.57 & -14.6 & -4.3 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} r \\ \beta \\ p \\ \Phi \end{bmatrix} + \begin{bmatrix} 0.04 & -2.6 \\ 0 & 0.04 \\ -12.4 & 1.8 \\ 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} \xi \\ \zeta \end{bmatrix}$$

The Classic View on Flight Control

Simulink implementation of the process dynamics (“physical part”)

Atmosphere
- Static atmosphere
- Dynamic atmosphere

Earth model
- WGS 84 ellipsoid
- Round earth
- Rotating / Nonrotating

Magnetic field
- World Magnetic Model

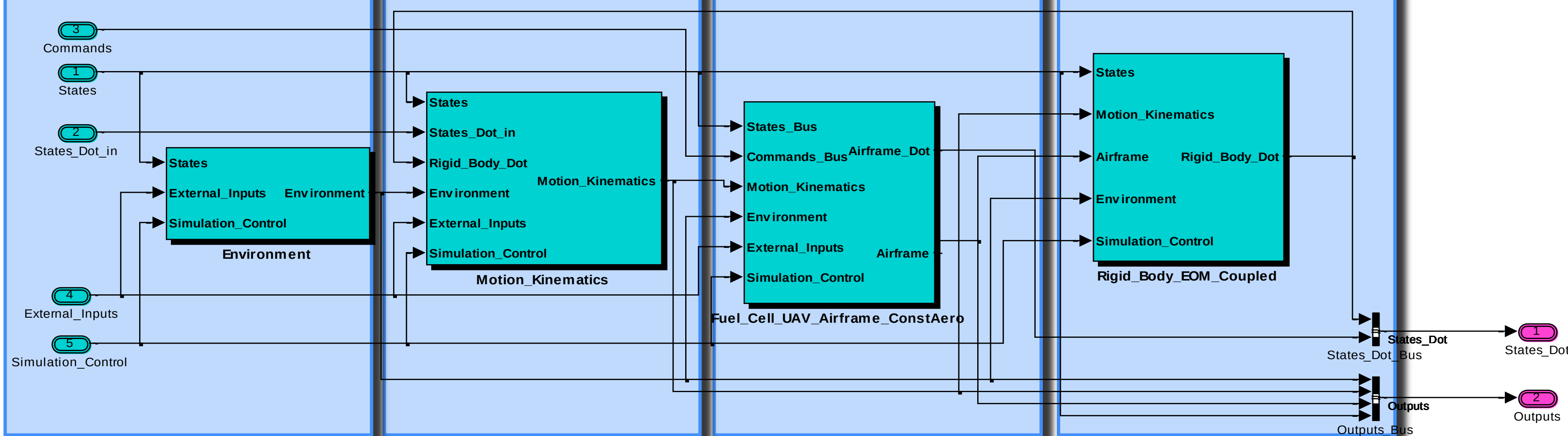
Gravity
- Somigliana

Transformations
- Kinematic relations
- Avoid redundand computation

External Forces
- Aerodynamic f&m
- Propulsion f&m

Subsystems
- Actuation
- Propulsion system
- Landing Gear
- Sensors
- Avionics
- Electrical system
- Hydraulics, fuel, …

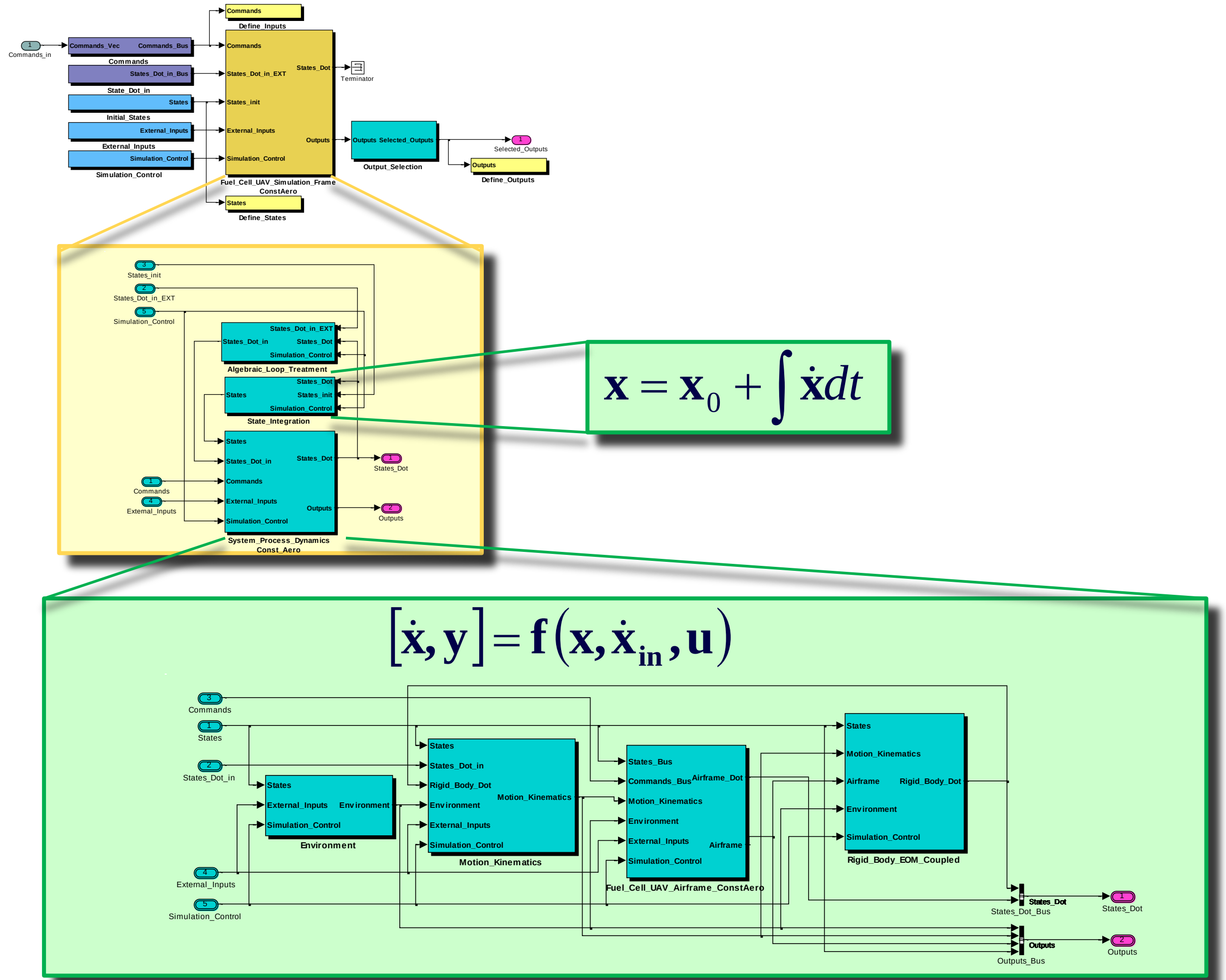
Equations of Motion
- Translation
- Rotation
- Attitude
- Position



- Top Level with interfaces to design, analysis and optimization tools
(one model fits all purposes)

- Separation of
system process dynamics and
time integration
(don‘t forget
single point execution)

- Modular process dynamics model $\Rightarrow$ fast adaption to new projects/applications
(independence from specific configuration)



The Classic View on Flight Control

Parameter Pre-Estimation – Model structure is easy, parameters are hard

- Aerodynamics
- Propulsion
- Control Surface Actuators
- Power Supply
- Weight and Balance
- Landing Gear
- High Lift Devices
- …


http://fcaap.com/index.cfm?p=research&p2=research&focus=air_vehicles

The Classic View on Flight Control

Parameter Pre-Estimation – The usual problem: forces and moments (aero&prop)

- Contribution to the dynamic system

$$\left(\dot{\vec{\mathbf{V}}}_K^G\right)_B^{EB} = \frac{\sum\left(\vec{\mathbf{F}}^G\right)_B}{m} - \left\{\left(\vec{\boldsymbol{\omega}}_K^{EB}\right)_B \times \left(\vec{\mathbf{V}}_K^G\right)_B^E + 2\cdot\left(\vec{\boldsymbol{\omega}}_K^{IE}\right)_B \times \left(\vec{\mathbf{V}}_K^G\right)_B^E + \left(\vec{\boldsymbol{\omega}}_K^{IE}\right)_B \times \left[\left(\vec{\boldsymbol{\omega}}_K^{IE}\right)_B \times \left(\vec{\mathbf{r}}^G\right)_B\right]\right\}$$

$$\left(\dot{\vec{\boldsymbol{\omega}}}_K^{IB}\right)_B^B = \left(\mathbf{I}^G\right)_{BB}^{-1} \cdot \left[\sum\left(\vec{\mathbf{M}}^G\right)_B - \left(\vec{\boldsymbol{\omega}}_K^{IB}\right)_B \times \left(\mathbf{I}^G\right)_{BB} \cdot \left(\vec{\boldsymbol{\omega}}_K^{IB}\right)_B\right]$$

- Modelling with the help of nondimensional coefficients

$$\left(\vec{\mathbf{F}}_A^A\right)_A = \begin{bmatrix} X_A^A \\ Y_A^A \\ Z_A^A \end{bmatrix}_A = \begin{bmatrix} -D \\ Q \\ -L \end{bmatrix} = \bar{q}\cdot S\cdot \begin{bmatrix} -C_D \\ C_Q \\ -C_L \end{bmatrix} \qquad \left(\vec{\mathbf{M}}_A^A\right)_B = \begin{bmatrix} L_A^A \\ M_A^A \\ N_A^A \end{bmatrix}_B = \bar{q}\cdot S\cdot \begin{bmatrix} s\cdot C_l \\ \bar{c}\cdot C_m \\ s\cdot C_n \end{bmatrix}$$

- Consideration of a reduced set of dependencies

$$C_L = C_L\left(\alpha_A, \beta_A, p^*, q^*, r^*, \dot{\alpha}_A, \dot{\beta}_A, \xi, \eta, \zeta, \delta_{Spoiler}, \delta_{Flaps}, M, R\right)$$

$$\Rightarrow \quad C_L = C_{L0} + C_{L\alpha}\cdot(\alpha-\alpha_0) + C_{Lq}\cdot\left(q^* - q_0^*\right) + C_{L\eta}\cdot(\eta-\eta_0) + \ldots$$

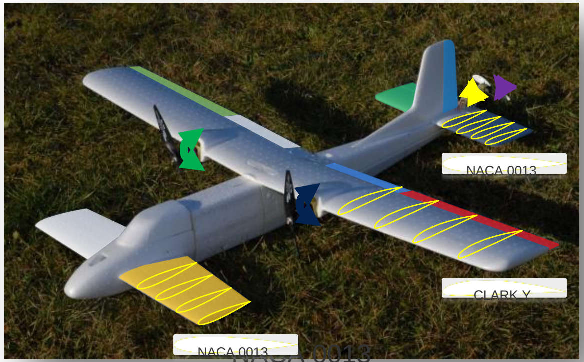
- Don’t overpower (Navier-Stokes, …)
- Understand the rationale, the math and the physics behind the method
- Know the weaknesses and shortcomings of the method
- Check underlying assumptions and prerequisites (aspect ratio, speed, …) – scope of validity
- Don’t trust tools
- Critically assess and question the results
- Use analytic approximations and scaled data for checking plausibility
- Use more than one method and analyze scatter
- Always be conservative and use worst-case
- Typical methods:

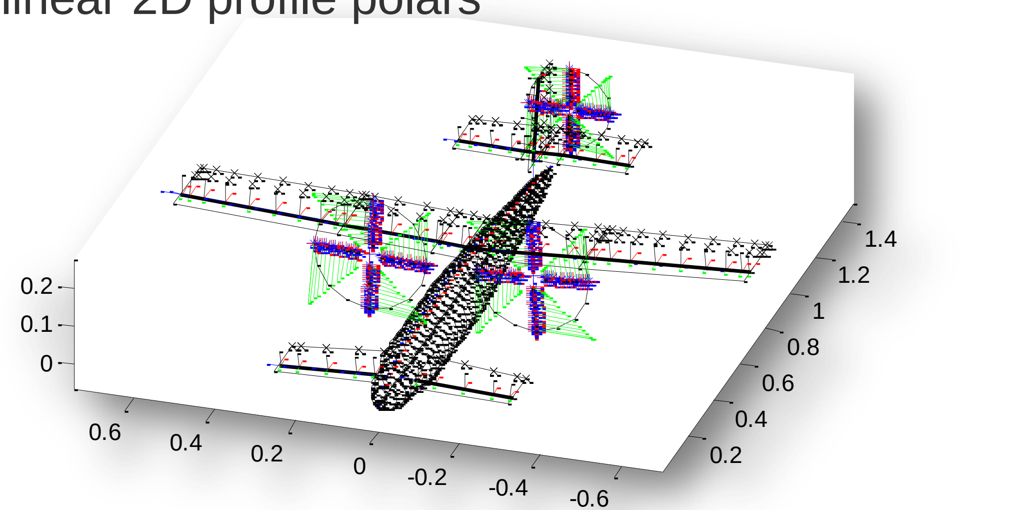
  Lifting line, lifting line with nonlinear profile aero, panel, empirical (DATCOM, AAA, Roskam), low-fidelity CFD

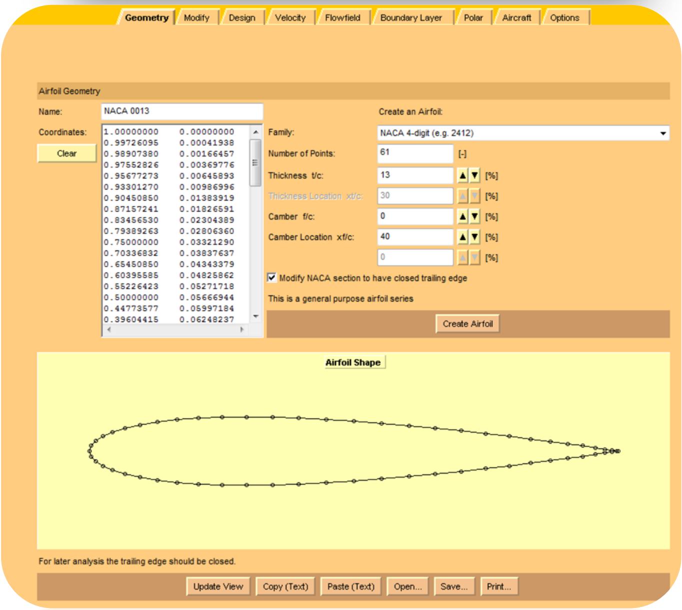
The results are always colorful – but are they correct and representative?

The Classic View on Flight Control
Parameter Pre-Estimation – Initial Aerodynamic Data

Example – linear lifting line with nonlinear 2D profile polars
consideration of rotating parts

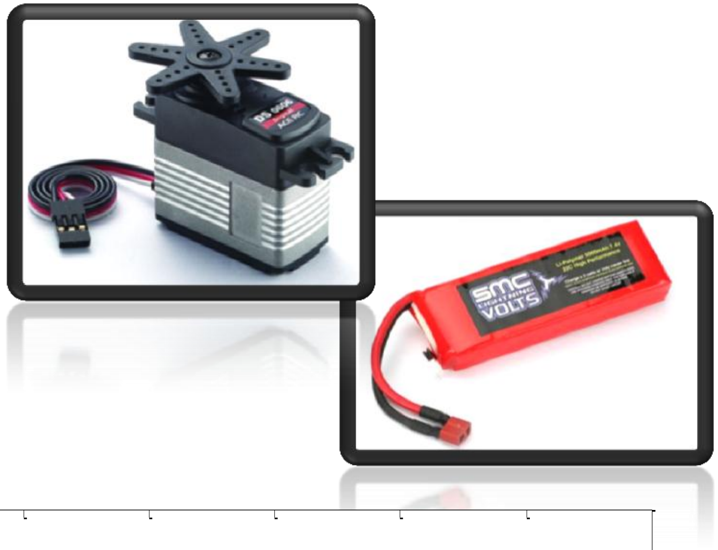






Modeling as second order transfer function

$$\ddot{\Phi} + 2\zeta\omega_0\dot{\Phi} + \omega_0^2\Phi = \omega_0^2 u$$

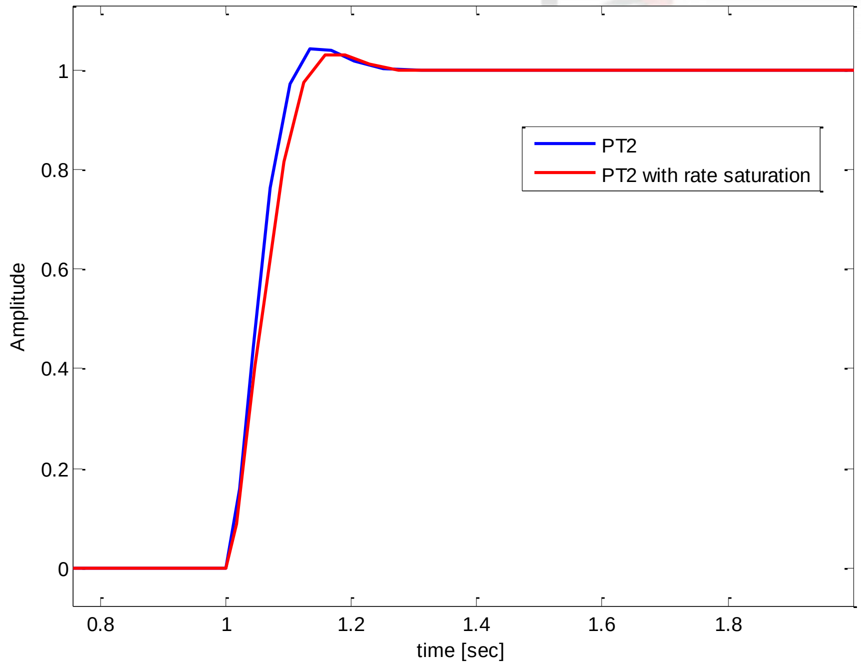


Identification of actuator parameters

- Damping
- Natural Frequency

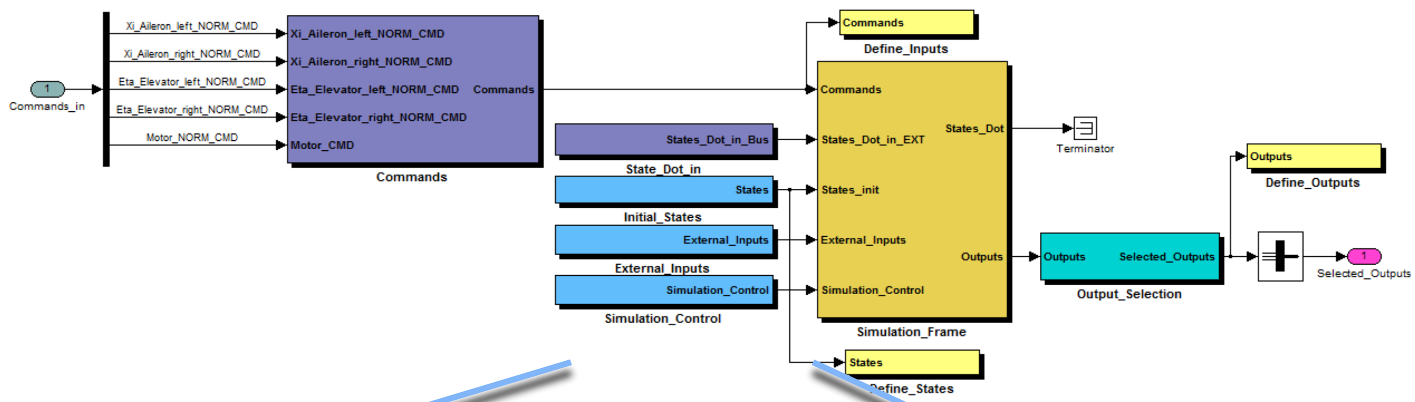
Introduction of typical nonlinearities

- angular acceleration saturation
- rate saturation
- position saturation
- gear backlash
- time delay



The Classic View on Flight Control

Work Flow: Trim–Linearize–Analyze–Design–Compute–Assess – Implement



Trimming
Determination of
steady state flight conditions

Linearization
Determination of linear state space
models

Flight Performance Analysis
Flight Envelope
Achievable Performance
Optimum flight conditions

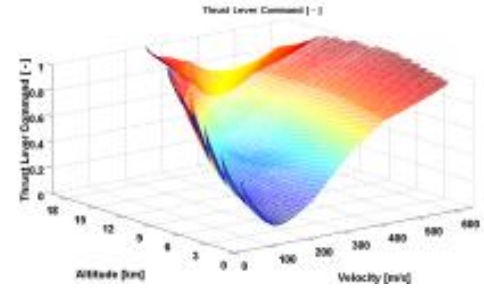
Flight Dynamics Analysis:
Eigenmodes,
Transfer Functions
Stability Properties
...

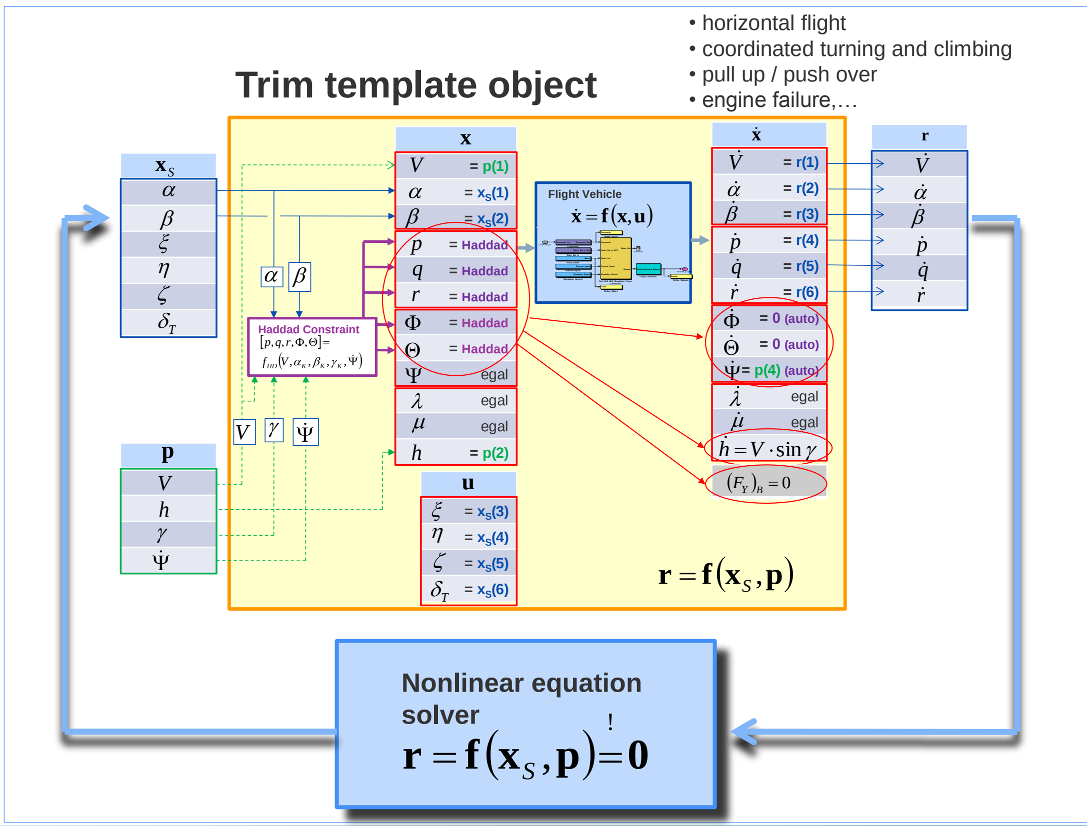
Automatic numerical gain design (Determination of Controller Gains)

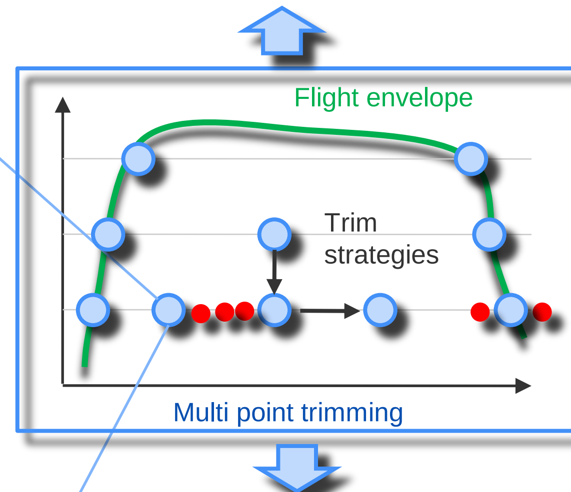
Flight Control Algorithm

The Classic View on Flight Control
Automated trim and performance assessment

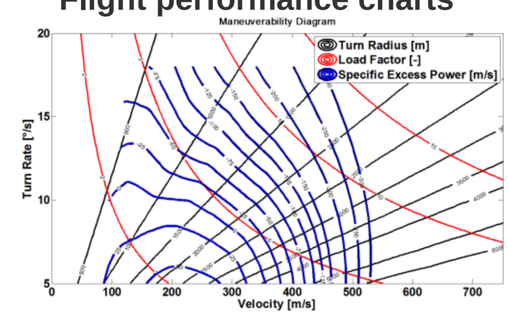
- Trim and flight mechanics tool
  - Efficient and robust algorithms for **steady state trim condition** determination
  - Multi point (grid) trimming with enhanced **trim strategies**
  - Determination of **flight envelope**
  - Automated generation of **flight performance charts**





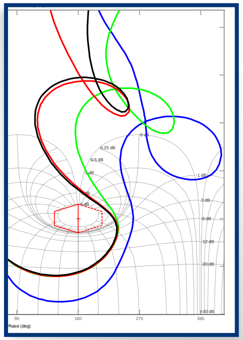


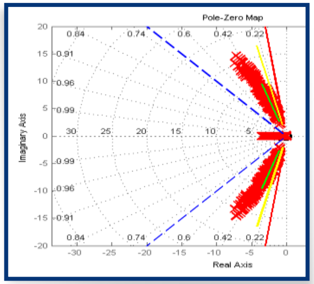
Flight performance charts

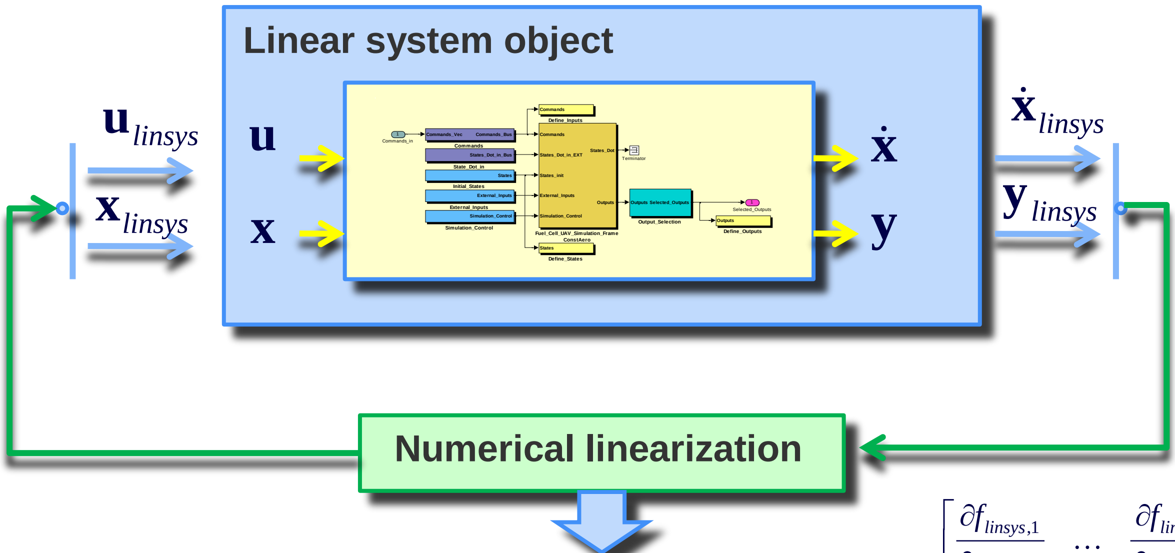


The Classic View on Flight Control
Automated linearization and stability & control assessment

- Efficient and robust algorithms for the extraction of linear state space model in trim conditions
- Numerical differentiation
- Linear system analysis
- Automated assessment of flying qualities



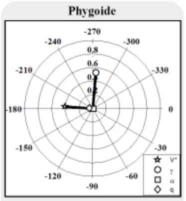




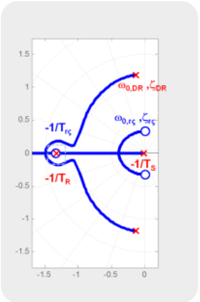
$$\dot{\mathbf{x}}_{linsys} = \mathbf{A}\mathbf{x}_{linsys} + \mathbf{B}\mathbf{u}_{linsys}$$

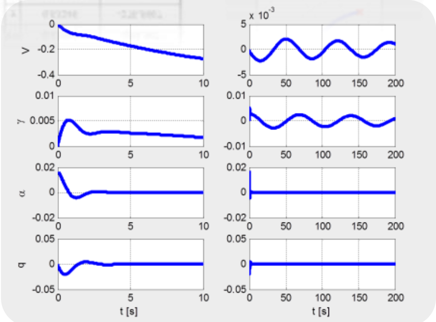
$$\mathbf{y}_{linsys} = \mathbf{C}\mathbf{x}_{linsys} + \mathbf{D}\mathbf{u}_{linsys}$$

$$\mathbf{A} = \begin{bmatrix} \frac{\partial f_{linsys,1}}{\partial x_{linsys,1}} & \cdots & \frac{\partial f_{linsys,1}}{\partial x_{linsys,n}} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_{linsys,n}}{\partial x_{linsys,1}} & \cdots & \frac{\partial f_{linsys,n}}{\partial x_{linsys,n}} \end{bmatrix}$$



	|x|	arg(x) [°]
V*	0.41054	-183.307
γ	0.53246	-275.5667
α	0.0094243	0
q	0.047576	-184.8106





The Classic View on Flight Control

Linear state-space models: Aircraft pitch dynamics

$$
\underbrace{\begin{bmatrix} \dot V \\ \dot\gamma \\ \dot\alpha \\ \dot q \\ \dot h \\ \dot x \end{bmatrix}}_{\dot{\mathbf{x}}(t)} =
\underbrace{\begin{bmatrix}
X_V - \frac{X_{\dot\alpha}\cdot Z_V}{Z_{\dot\alpha}-1} & \frac{g}{V_0}\sin\gamma_0\cdot\frac{X_{\dot\alpha}}{Z_{\dot\alpha}-1} - g\cos\gamma_0 & X_\alpha - \frac{X_{\dot\alpha}\cdot Z_\alpha}{Z_{\dot\alpha}-1} & \frac{Z_q\cdot X_{\dot\alpha} + X_{\dot\alpha} + X_q - X_q\cdot Z_{\dot\alpha}}{1-Z_{\dot\alpha}} & X_h - \frac{X_{\dot\alpha}\cdot Z_h}{Z_{\dot\alpha}-1} & 0 \\
\frac{Z_V}{Z_{\dot\alpha}-1} & \frac{g}{V_0}\sin\gamma_0\cdot\frac{1}{1-Z_{\dot\alpha}} & \frac{Z_\alpha}{Z_{\dot\alpha}-1} & \frac{Z_{\dot\alpha}+Z_q}{Z_{\dot\alpha}-1} & \frac{Z_h}{Z_{\dot\alpha}-1} & 0 \\
\frac{-Z_V}{Z_{\dot\alpha}-1} & \frac{g}{V_0}\sin\gamma_0\cdot\frac{1}{Z_{\dot\alpha}-1} & \frac{-Z_\alpha}{Z_{\dot\alpha}-1} & \frac{Z_q+1}{1-Z_{\dot\alpha}} & \frac{-Z_h}{Z_{\dot\alpha}-1} & 0 \\
M_V - \frac{M_{\dot\alpha}\cdot Z_V}{Z_{\dot\alpha}-1} & \frac{g}{V_0}\sin\gamma_0\cdot\frac{M_{\dot\alpha}}{Z_{\dot\alpha}-1} & M_\alpha - \frac{M_{\dot\alpha}\cdot Z_\alpha}{Z_{\dot\alpha}-1} & \frac{Z_q\cdot M_{\dot\alpha} + M_{\dot\alpha} + M_q - M_q\cdot Z_{\dot\alpha}}{1-Z_{\dot\alpha}} & M_h - \frac{M_{\dot\alpha}\cdot Z_h}{Z_{\dot\alpha}-1} & 0 \\
\sin\gamma_0 & V_0\cos\gamma_0 & 0 & 0 & 0 & 0 \\
\cos\gamma_0 & -V_0\sin\gamma_0 & 0 & 0 & 0 & 0
\end{bmatrix}}_{\mathbf{A}} \cdot
\underbrace{\begin{bmatrix} V \\ \gamma \\ \alpha \\ q \\ h \\ x \end{bmatrix}}_{\mathbf{x}(t)} +
\underbrace{\begin{bmatrix}
X_\eta - \frac{X_{\dot\alpha}\cdot Z_\eta}{Z_{\dot\alpha}-1} & X_{\delta_T} - \frac{X_{\dot\alpha}\cdot Z_{\delta_T}}{Z_{\dot\alpha}-1} \\
\frac{Z_\eta}{Z_{\dot\alpha}-1} & \frac{Z_{\delta_T}}{Z_{\dot\alpha}-1} \\
\frac{Z_\eta}{1-Z_{\dot\alpha}} & \frac{Z_{\delta_T}}{1-Z_{\dot\alpha}} \\
M_\eta - \frac{M_{\dot\alpha}\cdot Z_\eta}{Z_{\dot\alpha}-1} & M_{\delta_T} - \frac{M_{\dot\alpha}\cdot Z_{\delta_T}}{Z_{\dot\alpha}-1} \\
0 & 0 \\
0 & 0
\end{bmatrix}}_{\mathbf{B}} \cdot
\underbrace{\begin{bmatrix} \eta \\ \delta_T \end{bmatrix}}_{\mathbf{u}(t)}
$$

$$X_V \approx -\frac{\bar q_0 S}{m V_0}\cdot\left[M_0\cdot\left.\frac{\partial C_D}{\partial M}\right|_0 + 2C_D|_0\right]$$

$$X_\alpha \approx \frac{\bar q_0 S}{m}\cdot\left[C_L|_0 - C_{D\alpha}\right]$$

$$X_q = -\frac{\bar q_0 S}{m}\cdot\frac{\bar c}{2V_0}\cdot C_{Dq}$$

$$X_h \approx -\frac{\bar q_0 S}{m\rho_0}\cdot\left.\frac{\partial\rho}{\partial h}\right|_0\cdot C_D|_0$$

$$X_{\dot\alpha} \approx -\frac{\bar q_0 S}{m}\cdot\frac{\bar c}{2V_0}\cdot C_{D\dot\alpha}$$

$$X_\eta = -\frac{\bar q_0 S}{m}\cdot C_{D\eta}$$

$$X_{\delta_T} = \frac{1}{m}\cdot\left[\left.\frac{\partial (X_P)_B}{\partial\delta_T}\right|_0\cos\alpha_0 + \left.\frac{\partial (Z_P)_B}{\partial\delta_T}\right|_0\sin\alpha_0\right]$$

$$Z_V \approx -\frac{\bar q_0 S}{m V_0^2}\cdot\left[M_0\cdot\left.\frac{\partial C_L}{\partial M}\right|_0 + 2C_L|_0\right]$$

$$Z_\alpha \approx -\frac{\bar q_0 S}{m V_0}\cdot\left[C_{L\alpha} + C_D|_0\right]$$

$$Z_q = -\frac{\bar q_0 S}{m V_0}\cdot\frac{\bar c}{2V_0}\cdot C_{Lq}$$

$$Z_h \approx -\frac{\bar q_0 S}{m V_0\rho_0}\cdot\left.\frac{\partial\rho}{\partial h}\right|_0\cdot C_L|_0$$

$$Z_{\dot\alpha} \approx -\frac{\bar q_0 S}{m V_0}\cdot\frac{\bar c}{2V_0}\cdot C_{L\dot\alpha}$$

$$Z_\eta = -\frac{\bar q_0 S}{m V_0}\cdot C_{L\eta}$$

$$Z_{\delta_T} = -\frac{1}{m V_0}\cdot\left[\left.\frac{\partial (X_P)_B}{\partial\delta_T}\right|_0\sin\alpha_0 - \left.\frac{\partial (Z_P)_B}{\partial\delta_T}\right|_0\cos\alpha_0\right]$$

$$M_V \approx \frac{1}{I_{yy}}\cdot\frac{\bar q_0 S\bar c}{V_0}\cdot M_0\cdot\left.\frac{\partial C_m}{\partial M}\right|_0$$

$$M_\alpha \approx \frac{1}{I_{yy}}\cdot\bar q_0 S\bar c\cdot C_{m\alpha}$$

$$M_q = \frac{1}{I_{yy}}\cdot\bar q_0 S\bar c\cdot\frac{\bar c}{2V_0}\cdot C_{mq}$$

$$M_h \approx 0$$

$$M_{\dot\alpha} \approx \frac{1}{I_{yy}}\cdot\bar q_0 S\bar c\cdot\frac{\bar c}{2V_0}\cdot C_{m\dot\alpha}$$

$$M_\eta = \frac{1}{I_{yy}}\cdot\bar q_0 S\bar c\cdot C_{m\eta}$$

$$M_{\delta_T} = \frac{1}{I_{yy}}\cdot\left.\frac{\partial M_P^G}{\partial\delta_T}\right|_0$$

Thrust influence neglected

The Classic View on Flight Control

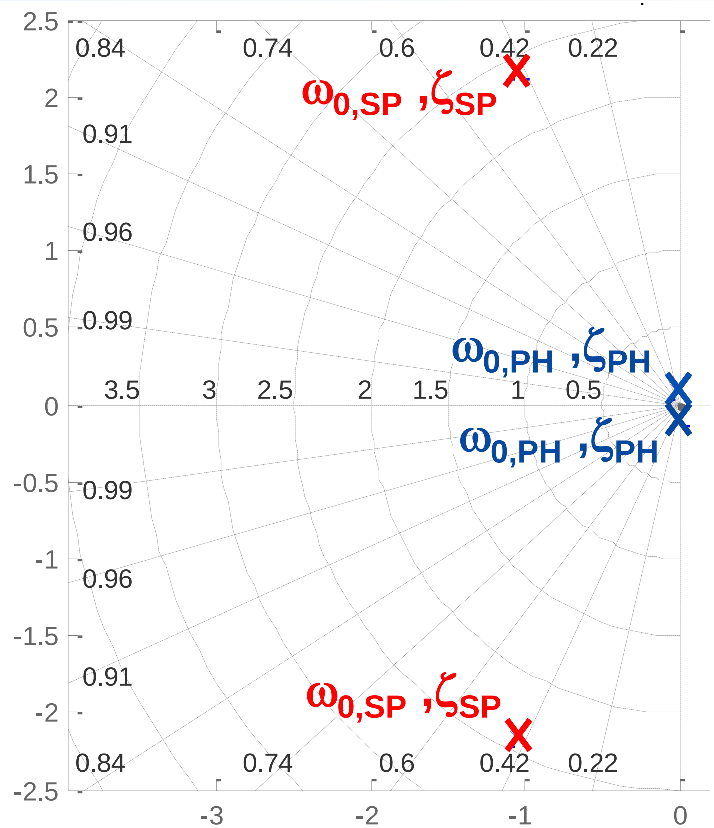
Linear Analysis – Eigenvalues: Aircraft Pitch Dynamics

Typical position of the Eigen Values of the longitudinal motion of a conventional aircraft in the complex plane:

Reference airplane and state data:

Airplane:	DC 8
Mach number:	0.443
Velocity:	142,6464 [m/s]
Weight:	86182,55 [kg]
Altitude:	4,57200 [km]

- **Two conjugate complex Eigen Value pairs**
  → Two periodic and stable Eigen motion forms
- **The two periodic Eigen motion forms differ strongly concerning their**



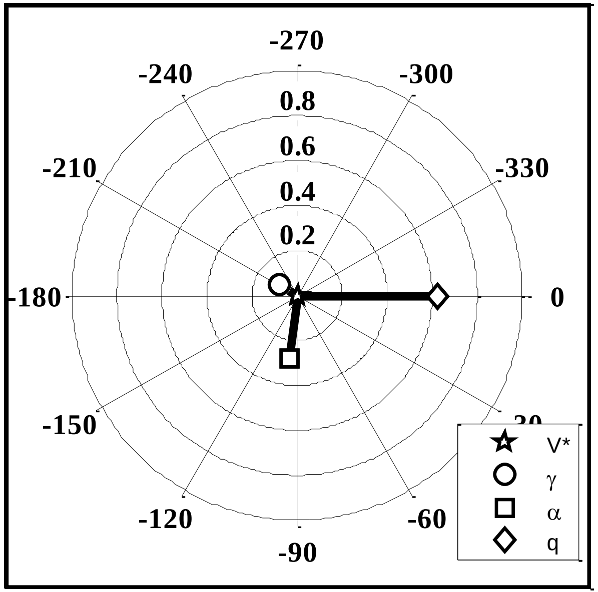
	Re(λ) [-]	Im(λ) [-]	ζ [-]	ω_0 [rad/s]
1	-0.0027447	0.089143	0.030776	0.089185
	-0.0027447	-0.089143	0.030776	0.089185
2	-1.043	2.1613	0.43462	2.3998
	-1.043	-2.1613	0.43462	2.3998

Long period (low frequency), weakly damped – **Phugoid mode (PH)**

Short period (high frequency), strongly damped – **Short Period mode (SP)**

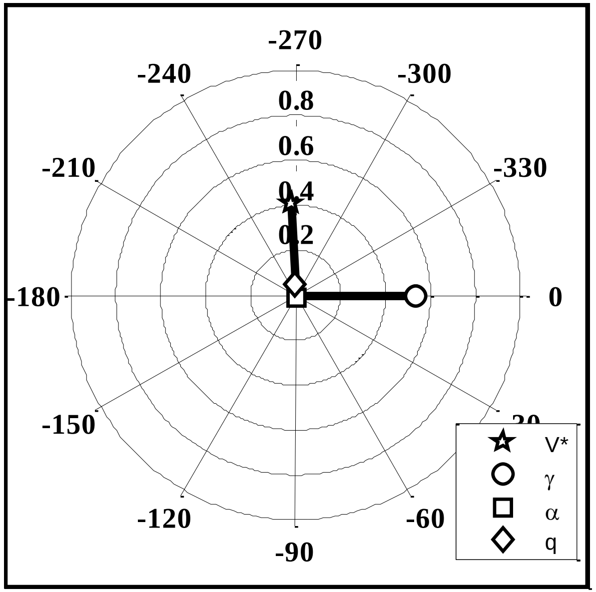
Linear Analysis – Eigenvectors: Aircraft Pitch Dynamics

Short-period mode



	|x|	arg(x) [°]
V*	0.0039838	-68.8305
γ	0.089972	-213.2013
α	0.28484	-97.5079
q	0.62121	0

Phugoid mode

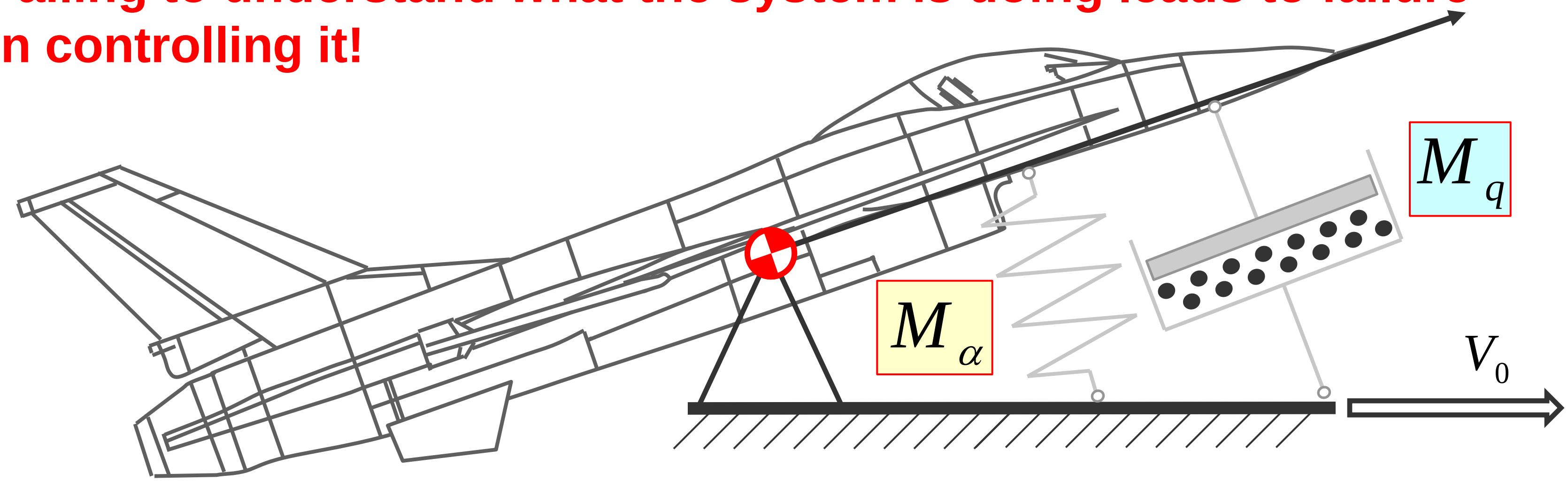


	|x|	arg(x) [°]
V*	0.41054	-267.7402
γ	0.53246	0
α	0.0094243	-84.4333
q	0.047576	-269.2439

⇨ **The states pitch rate and angle of attack are the main factors in the Short-period mode**

⇨ **The states velocity and climb angle are the main factors in the Phugoid mode**

For mastering real systems, correct math is a prerequisite – however not enough.
Failing to understand what the system is doing leads to failure in controlling it!



M_α corresponds to spring constant of a mass-spring-damper-system

M_q corresponds to damping coefficient of a mass-spring-damper-system

The Classic View on Flight Control

Control Objective – How should the aircraft behave? – Requirements

EASA CS 22/23/25/27/29/ VLA/VLR FAR 23/25/27/29/103

(Airworthiness Regulations)

„General, qualitatively requirements for airworthiness, for whose implementation the EASA reverts to MILs"

MIL-STD-1797A MIL-F-8785C

(Military Standard and Specification of „Flying Qualities for Piloted Aircraft")

„Quantitative requirements for the handling quality"

MIL-DTL-9490E

(Military Specification of „Flight Control Systems – Design, Installation and Test of Piloted Aircraft, General Specification")

„Stability- and robustness requirements for flight controllers as well as accurateness requirements for autopilots"

Secondary literature

(Papers, reports of expert groups, e.g. NATO RTO, Garteur, ...)

The Classic View on Flight Control

Control Objective – How should the aircraft behave? – Requirements

Concerning the function of the aircraft it is allocated to one of the four classes:

Class I	Class II	Class III	Class IV
Small, light airplanes	Medium-weight, low-to-medium maneuverability airplanes	Large, heavy, low-to-medium maneuverability airplanes	High-maneuverability airplanes

Nonterminal Flight Phases

Category A

Require rapid maneuvering, precision tracking, or precise flight path control

e.g.

- Air-to-air combat (CO)
- Ground Attack (GA)
- Aerial recovery (AR)
- Reconnaissance (RC)

Category B

Normally accomplished using gradual maneuvers and without precision tracking, although accurate flight-path control may be required

e.g.

- Climb (CL)
- Cruise (CR)
- Descent (D)
- Emergency Descent (ED)

Terminal Flight Phases

Category C

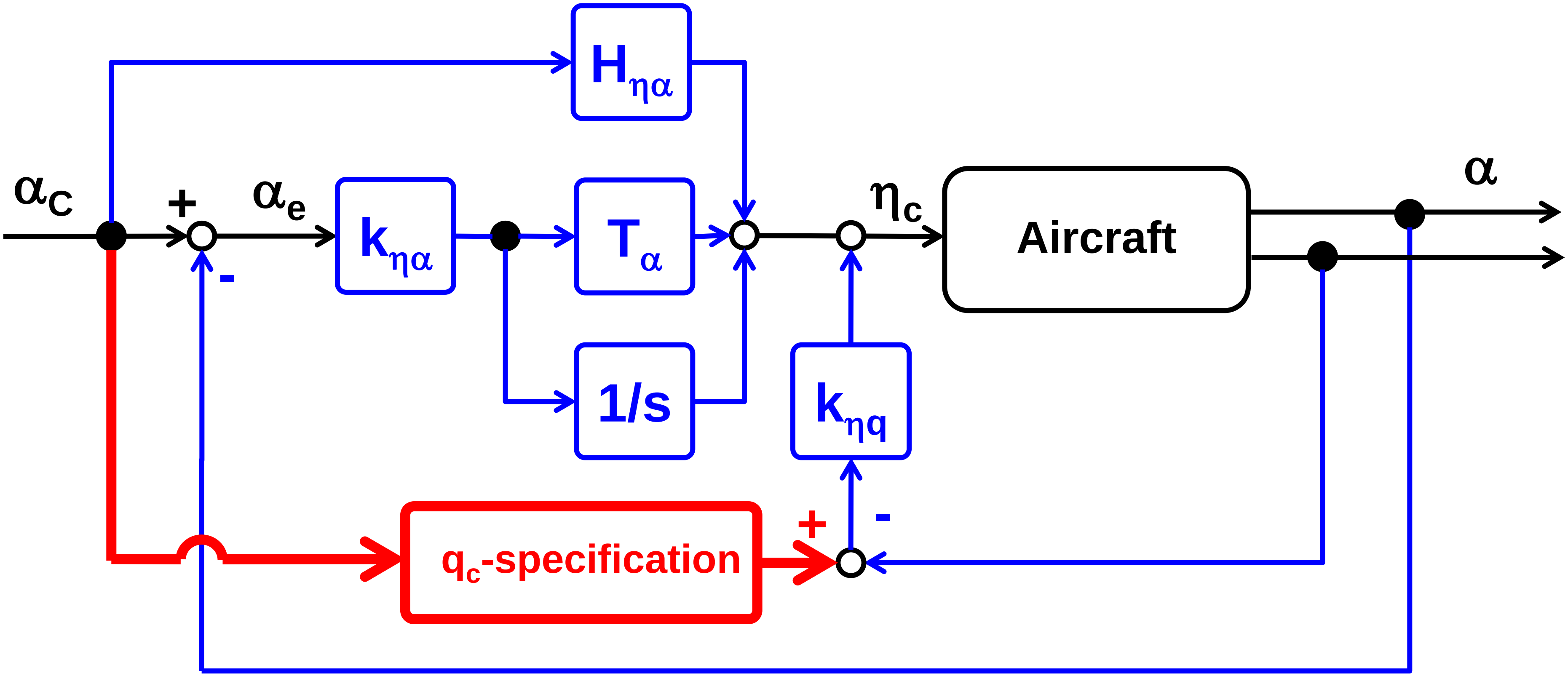
Normally accomplished using gradual maneuvers and usually require accurate flight-path control.

e.g.

- Takeoff (TO)
- Approach (PA)
- Landing (L)

Physically motivated choice of controller structure: Classic aircraft inner loop (CSAS)

Angle of attack command and stability augmentation system

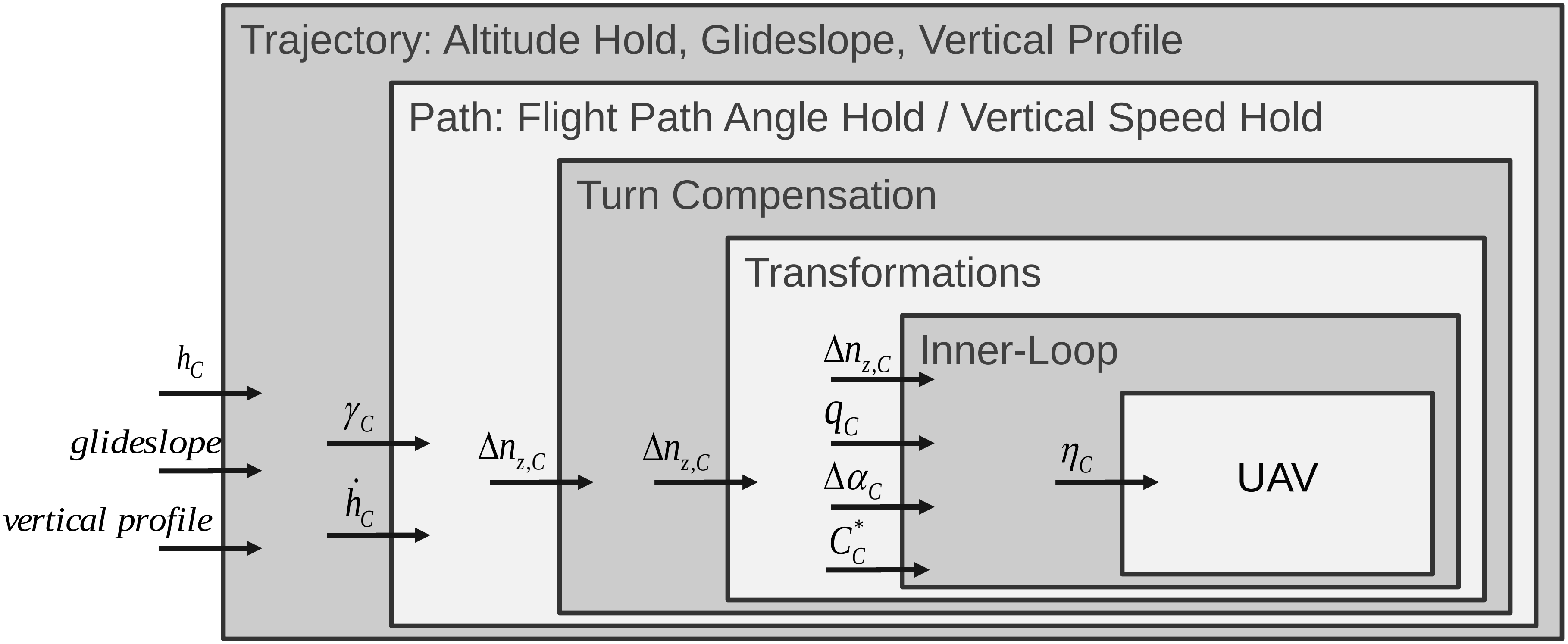


q_c - specification:

The pitch rate corresponding to the commanded α is computed.
The pitch damper is just feeding back the error in pitch rate, i.e. the deviation from the precomuted value.
By that it is ensured that the pitch damper will not fight the commanded maneuver.

The Classic View on Flight Control

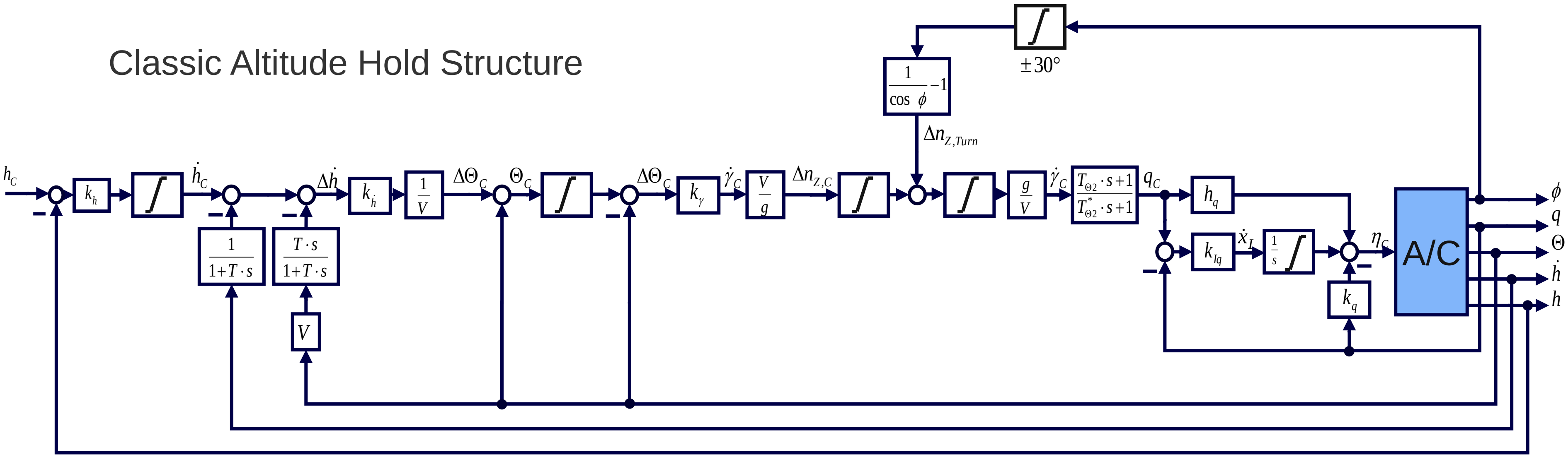
Hierarchical structure of classic autoflight systems: “Vertical plane control”



The Classic View on Flight Control

Hierarchical structure of classic autoflight systems: “Vertical plane control”

Classic Altitude Hold Structure



Attitude Control
- Heading hold
- Pitch hold
- Bank hold / Wings leveler

Flight-Path Control
- Vertical speed hold
- Flight Path Angle hold
- Course hold

Trajectory Control
- Altitude hold
- Track hold
- Waypoint Navigation

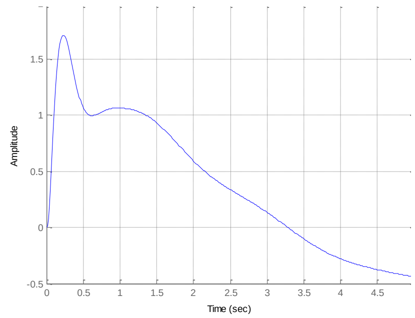
Speed Hold
- By elevator or thrust
- Indicated Airspeed Mach Number or Groundspeed

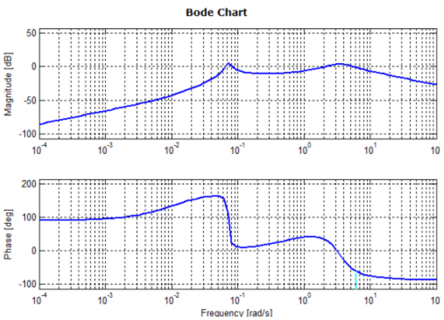
Automatic Landing
- Coupled approach
- Flare and Touch Down
- Roll to stop

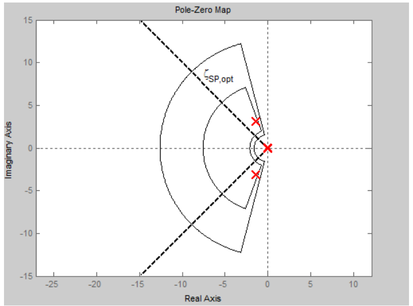
FMS
- Connection from flight phase to flight plan/ mission
- Consideration of weather, economy…

Analysis of open loop

- Time & frequency domain
- Eigenvalues / -vectors
- Pole zero distribution
- Stability, margins





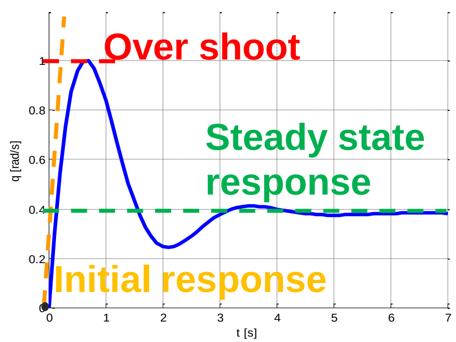


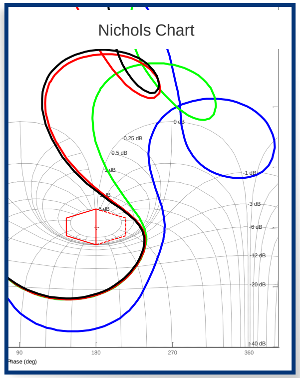
Gain design method

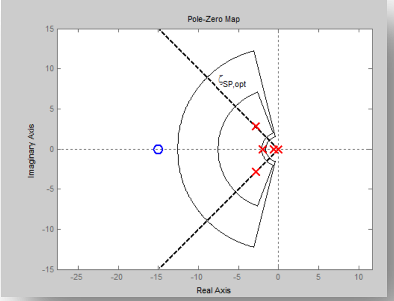
- Modal Control: SISO, MIMO pole placement, Eigenstructure assignment
- Optimal control: LQR / LQG
- Robust control: H-Infinity, Mu-Synthesis
- Multi objective parameter optimization

Closed loop criteria fullfilled ?

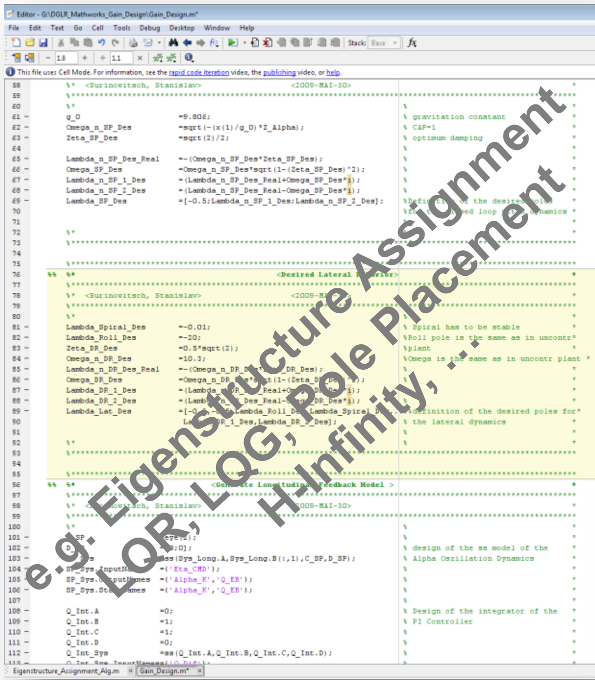
- Analysis and iterations
- Automation is a main issue!
- Not in a single point, but over the whole envelope

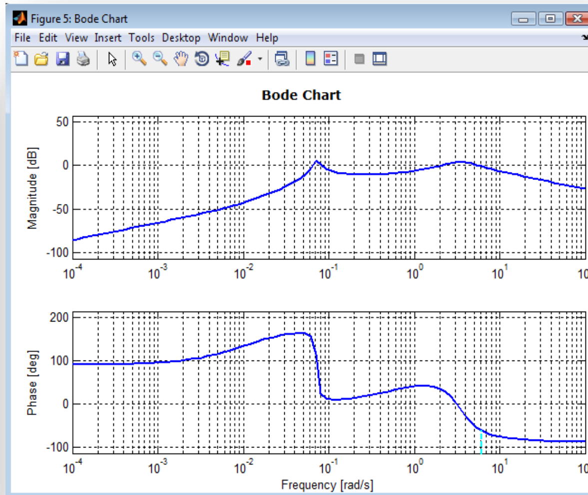


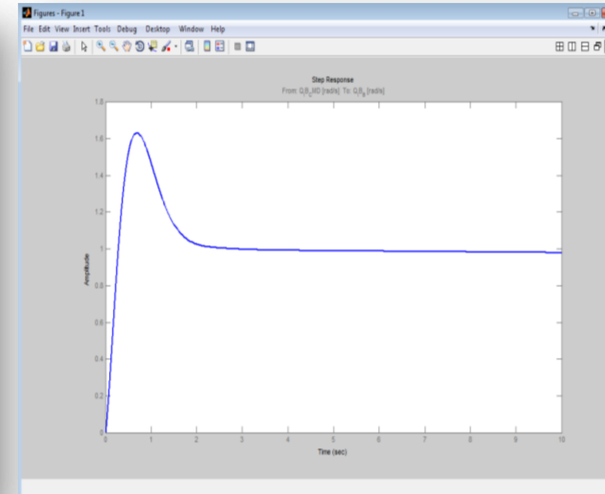


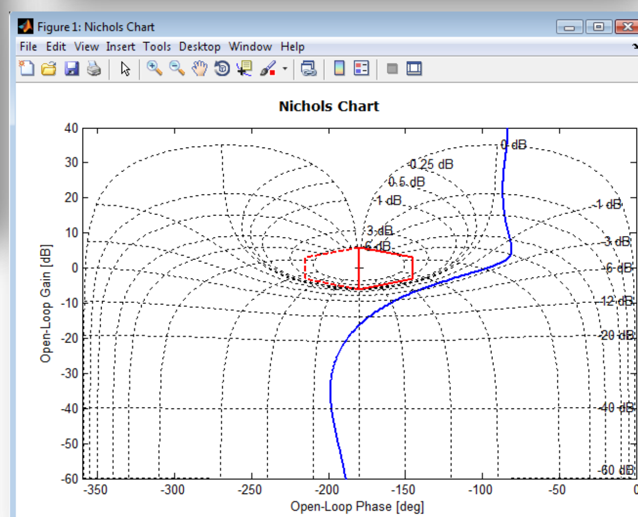


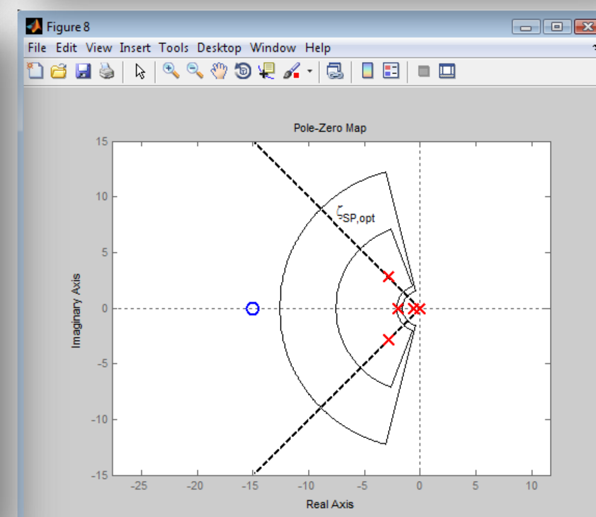
Designing the gains – automation of gain computation and closed-loop assessment





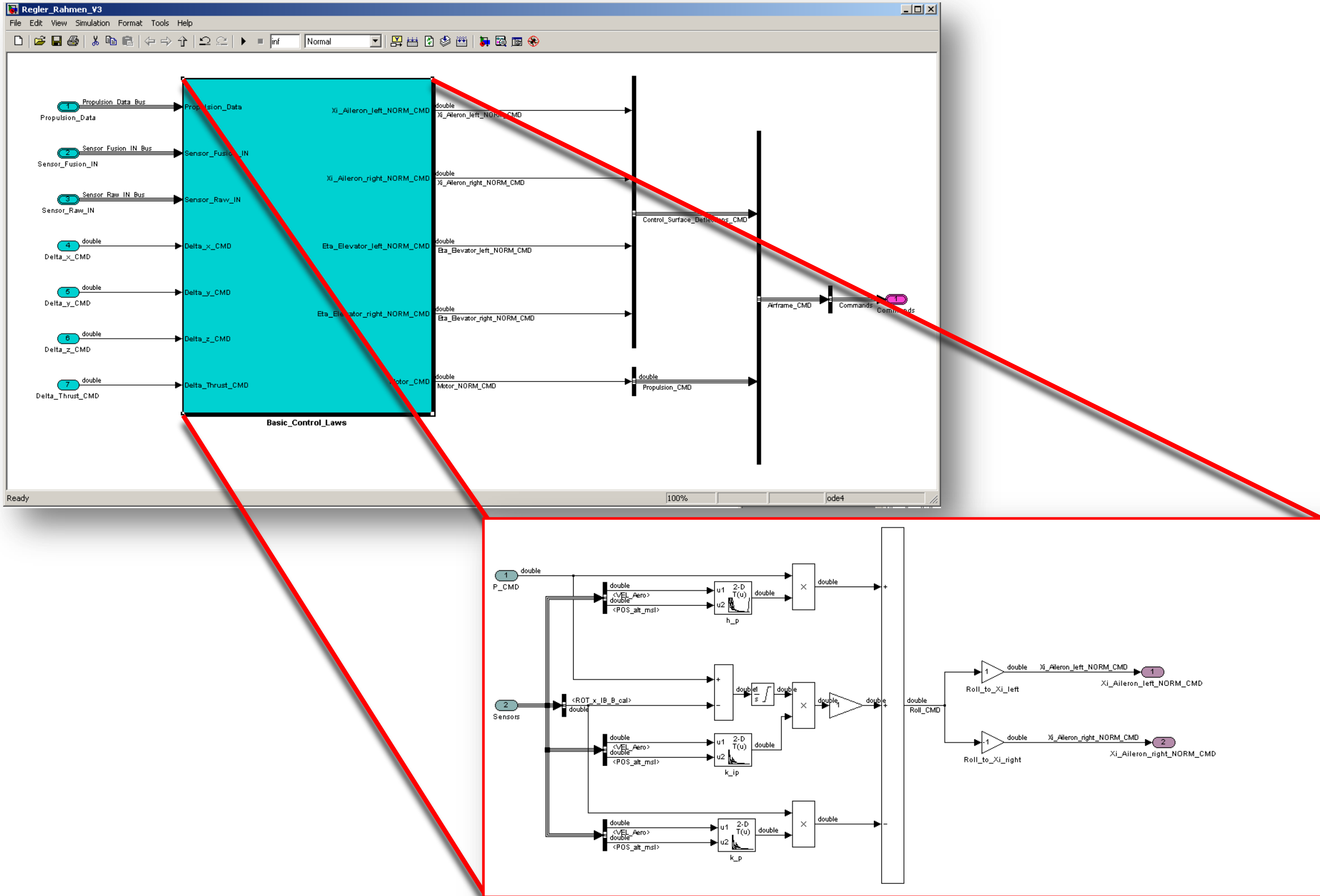






The Classic View on Flight Control

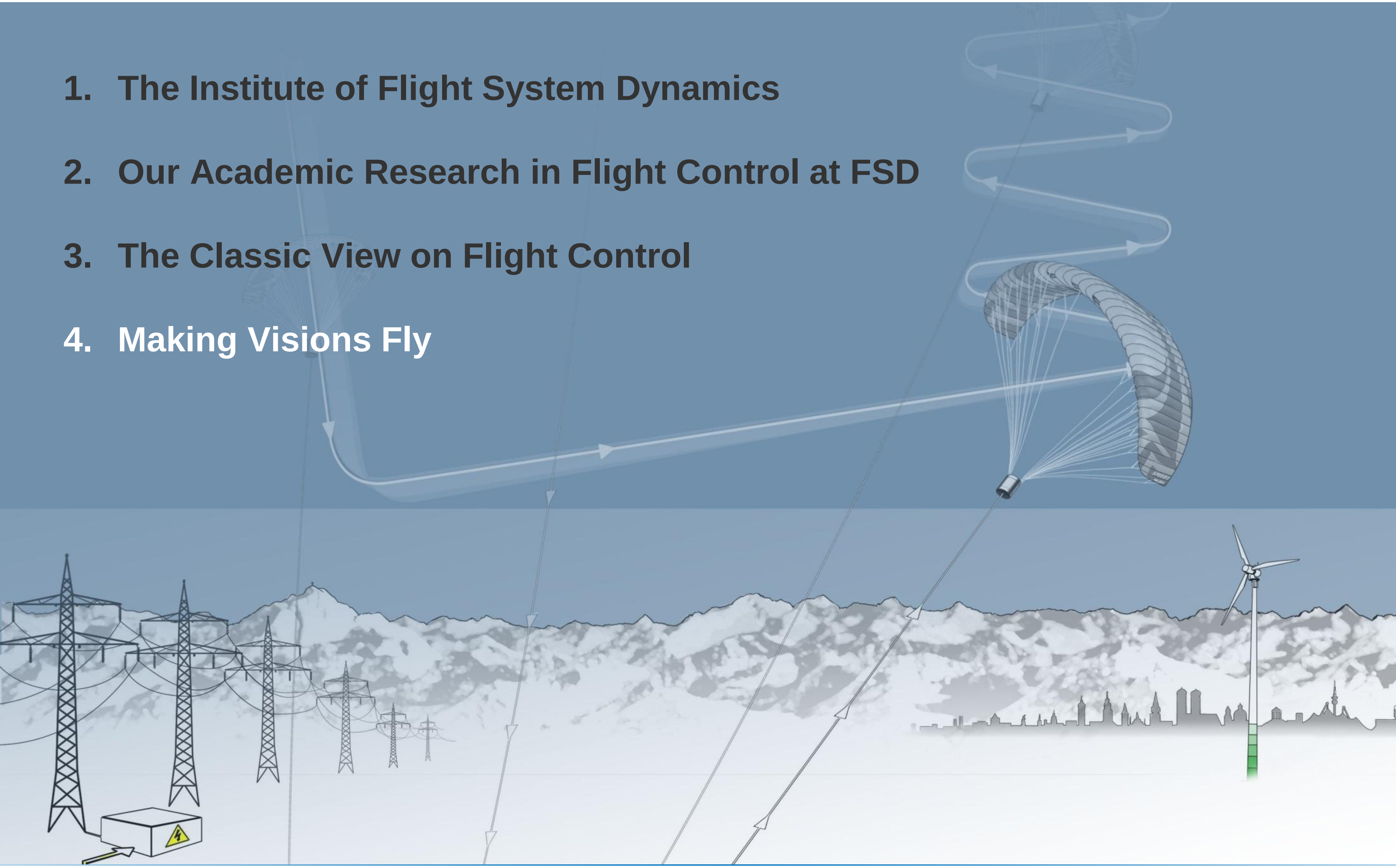
Implementing the controller: The controller used for design is not fit for the system



Video: Student Snail flying waypoints

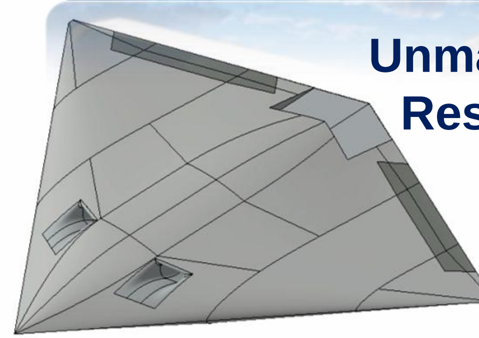
Outline

1. The Institute of Flight System Dynamics
2. Our Academic Research in Flight Control at FSD
3. The Classic View on Flight Control
4. **Making Visions Fly**



Making Visions Fly
Now things can go wrong

Unmanned Product



Unmanned Research

Consequences of Failure:
Loss of
money
property
life

Manned Product

Manned Research

Unmanned Research

- Failures lead to loss of money, property or life
- Public interest in safety ⇒ regulations („certification“)
- Operational systems need to be dependable
  Dependability = Safety + Reliability + Availability + Integrity
  - Safety: a measure of the absence of catastrophic consequences on user and environment
  - Reliability: a measure of the systems continuity of correct service
  - Availability: a measure of the systems readiness for correct service
  - Integrity: a measure of the absence of improper system alteration

- Many ideas successfully demonstrated in proofs of concept never made it to real products
- The earlier showstoppers for real application are identified and mitigated, the higher the chance for real application is

Making Visions Fly

Consequences for development, implementation and operation of flying systems

- Given characteristics have to be guaranteed with a given probability
- Adherence to these requirements must be proven and documented
- There is a tremendous gap between
  “what can be done” and “what may be done”
- The design is not driven by the nominal function but by failures
- Available potential has to be sacrificed for the sake of testability and the possibility to give proofs
- Very often, system performance is no longer the optimization goal –
  Required performance is boundary condition,
  operational robustness is optimization objective
- The “math” may no longer be considered standalone –
  physics, algorithms and implementation need to be addressed in an integrated manner

⇨ Traditionally, these points have been addressed by evolutionary steps and growing experience

⇨ However, revolutionary new concepts like HAWE systems cannot build on legacy experience

⇨ New approaches to answer the questions above are required

Multi-domain systems:

- System functionalities result from interactions between
  - **mechanical structures**,
  - **aircraft systems** (mechanic, hydraulic, electric, …) and
  - **avionics** (hard- & software)
- Highly dynamic systems with multiple inputs and multiple outputs
- Hard real time systems

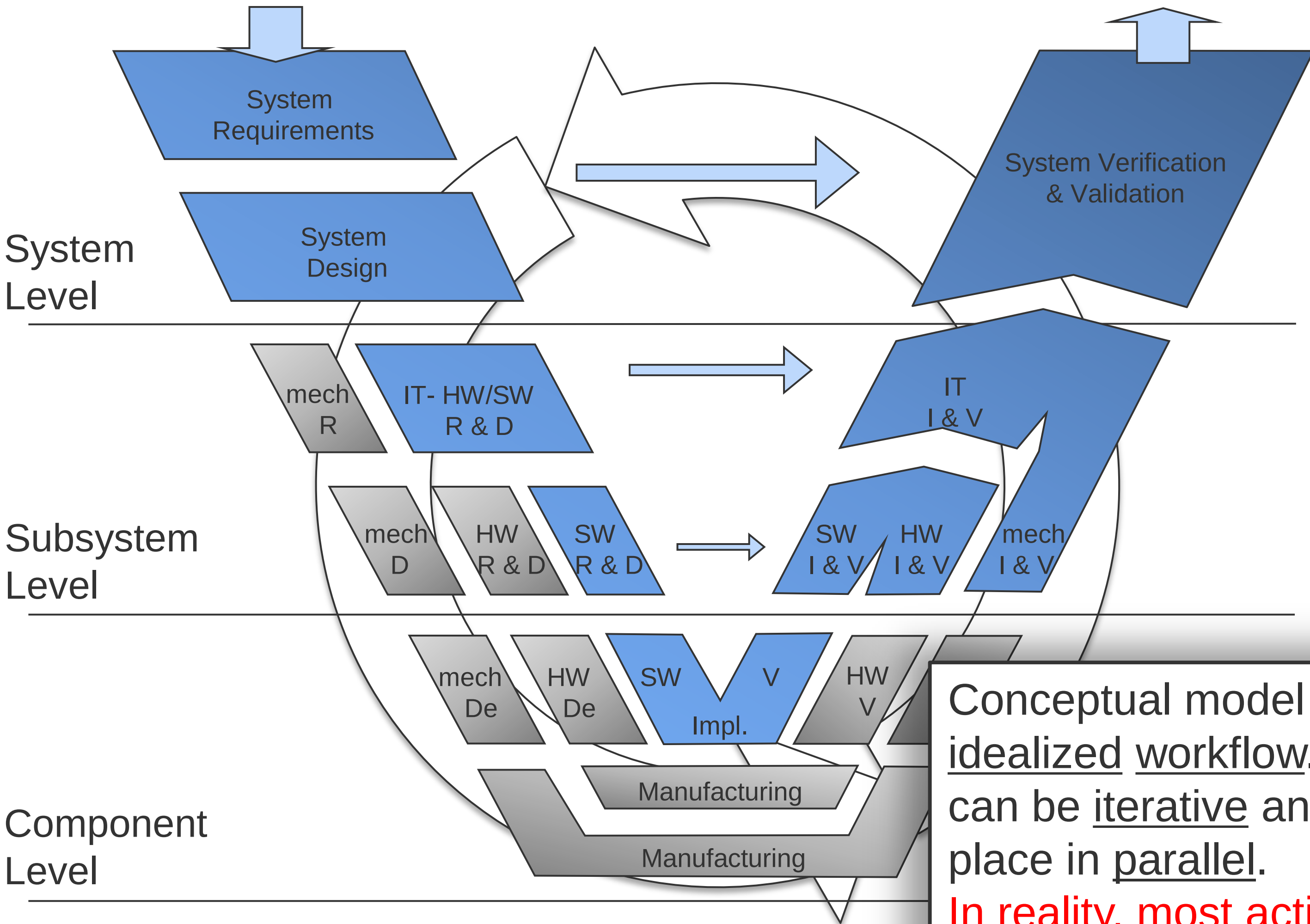
Approaches and methods in the different domains are dissimilar!
Every domain has specific and dissimilar methods, tools, …

- The assessment of flight control systems can only be carried out on the whole, integrated, closed-loop system!

- A proper system design relies on early deployment of a proper safety assessment process, so that possible failure modes are identified and treated in the design.

Making Visions Fly

The V-Model – between a “Bullshit Bingo Phrase” and a valuable guideline



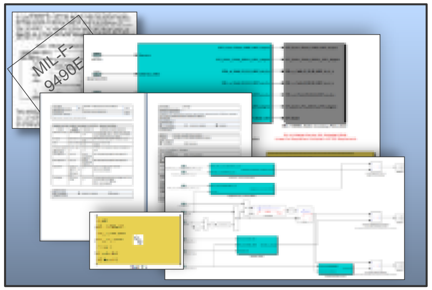
Conceptual model for logical, <u>idealized</u> <u>workflow</u>. Activities can be <u>iterative</u> and can take place in <u>parallel</u>.

In reality, most activities can not be handled sequentially !!!

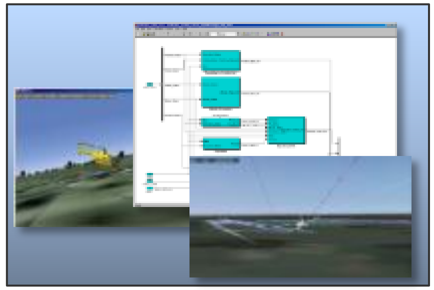
R Requirements
D Design
De Development
I Integration
V Verification & Validation

Making Visions Fly

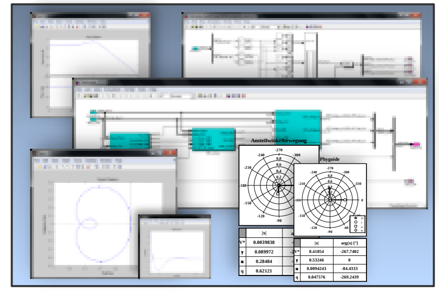
Model-based development – types and roles of models



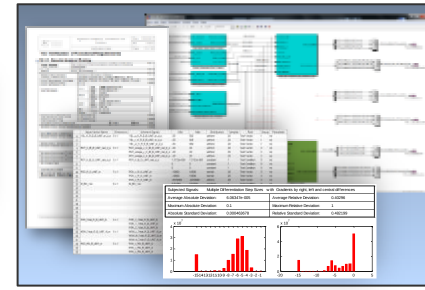
Requirement Models
(Formalized)



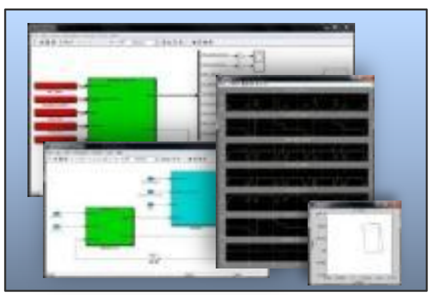
Plant Simulation
Models



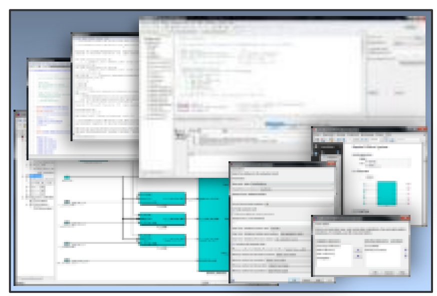
Algorithm Design
Models



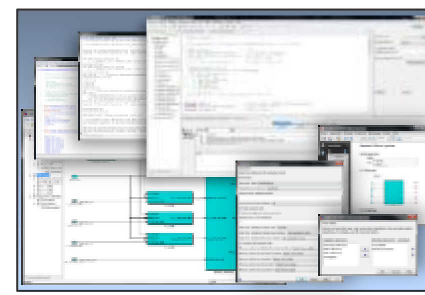
Validation &
Verification Models
(e.g. HIL/PIL Test Beds)



Virtual Prototypes,
Physical Models &
Other Models
(e.g. FTA)



Platform independent
Software Models
(Software Design)



Target Specific
Code Models
(Graphical Programming)

Making Visions Fly

Requirements – What do we want to develop

- Before developing something, the objectives and goals must be clear, complete, unique and non-contradictory
- It needs to be quantified before development of the system
  - What the design goal is ("Desired Performance")
  - What is considered as acceptable ("Adequate Performance")
  - How compliance is to be demonstrated ("Acceptable Means of Compliance")
- Therefore, all requirements must be quantified and formalized to be testable
- Normally, everybody considers functional requirements – however, there's much more:
  - Operational Requirements
  - Environmental Requirements
  - Safety Requirements
  - Many Derived Requirements (depending on the design)
  - …

Requirements Formulation for High Altitude Wind Energy Systems

- Handling qualities are well-known & established requirements for designing flight control algorithms in manned flight but not applicable to unmanned aerial vehicles!

- Absence of flight dynamics and stability requirements for design of flight control algorithms for UAV´s and thus HAWE's

- High Altitude Wind Energy Systems arise a complete new domain of flying systems, so where to get the requirements?

Approach:

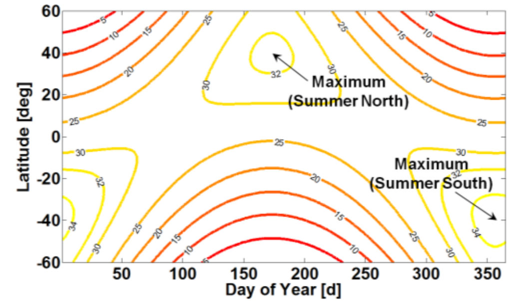
- Probabilistic Analyses in consideration of system uncertainties and typical stochastic systems errors (e.g. GPS position)

- Validation of high-level requirements w.r.t. flight dynamics and flight control

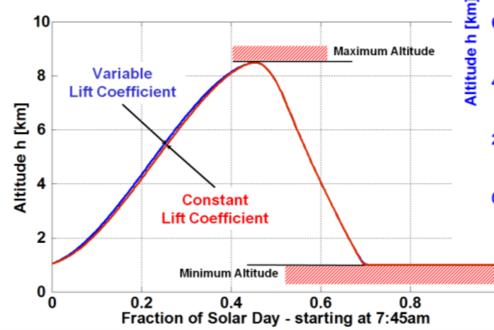
- Formulation of physically meaningful and consistent requirements for flight controller design of HAWE's respecting inherent aircraft dynamics

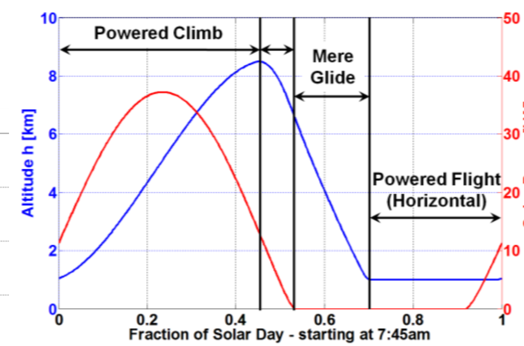
- How to operate a new system in a way that it delivers the maximum outcome?
  - ⇨ Optimization Problem!

Example: Solar Aircraft



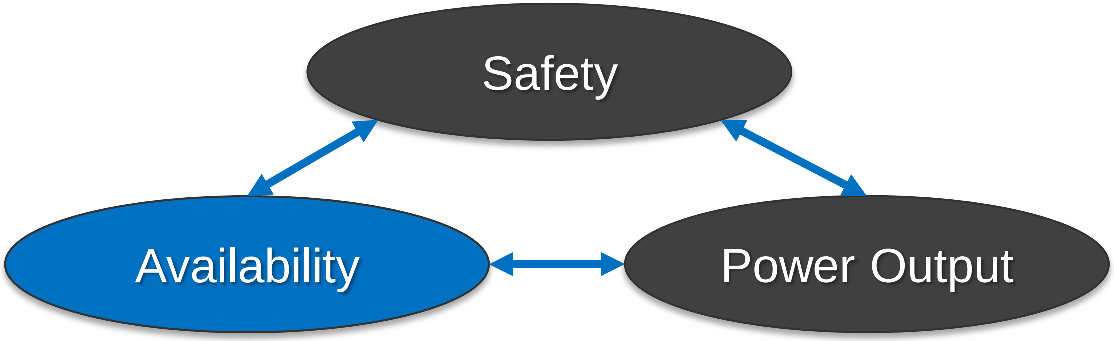
- Trajectory Optimization leads to optimal solutions under nominal conditions but is prone to disturbances and environmental influences
  - ⇨ Helpful to get a first “feeling” for the system





Identification of the high level design objectives of a HAWE-System leads to:

Optimization with respect to Availability!



Boundary Conditions:

⇨ Generation of a specific power output
⇨ Under given safety requirements

Availability means less sensitivity to disturbances and external influences!

Optimization under consideration of:

⇨ Flight phases during normal and emergency operation
⇨ Environmental conditions and influences
⇨ Failure scenarios
⇨ System and component specific behavior
⇨ Future certification

Why?

In early stages of the development life cycle information on aircraft rarely exists.

Most often requirements to subsystems of an aircraft (e.g. sensors, actuators, flight control system) are stated and quantified based on **assumptions** using expertize from prior projects or engineering judgement.

Overview about **interdependence** of requirements and their **consistency** and **correctness** can hardly be gained.

What?

Derivation of **physically motivated, quantified** and **consistent requirements** for aircraft subsystems and flight control.

How?

Simplified **mathematical descriptions** of aircraft flight dynamics including generic and aircraft specific information

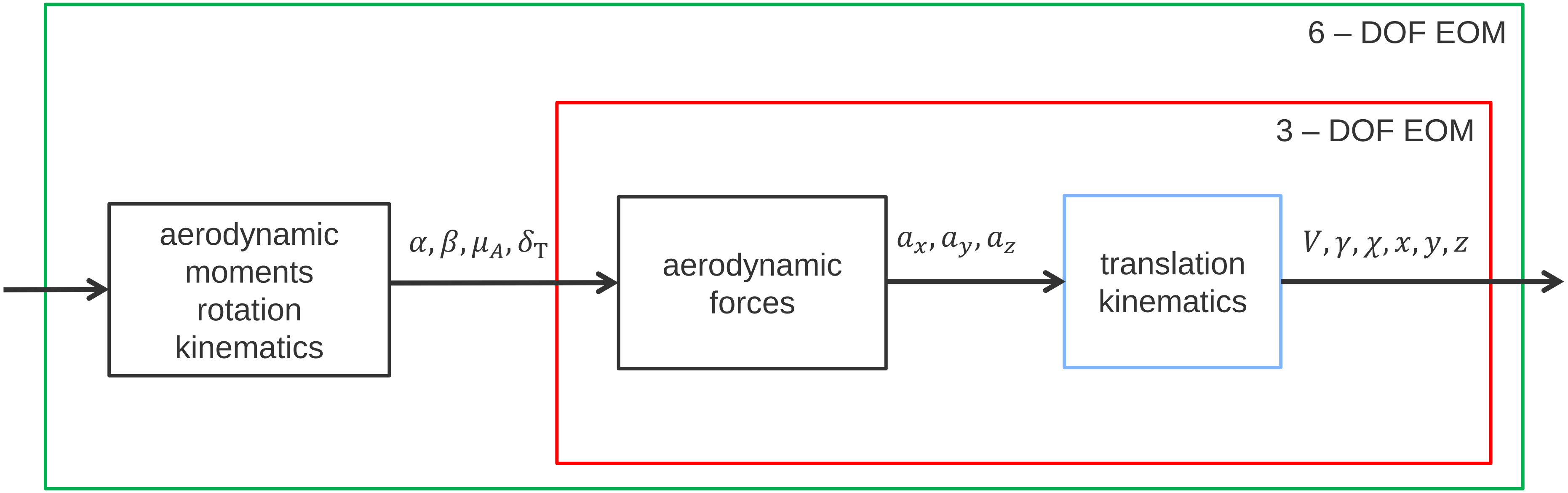
Flight mechanics models are powerful tools for determination of requirements in different stages of product development process and in different engineering domains.

Flight dynamics and systems specification:

- stability and performance analysis
- specification of subsystems performance (sensors, actuators, propulsion system)
- weight & balance (bookkeeping)
- envelope determination
- …

Flight control system specification

- specification of envelope protections and limitations
- specification of performance requirements
- specification of closed-loop behavior
- …

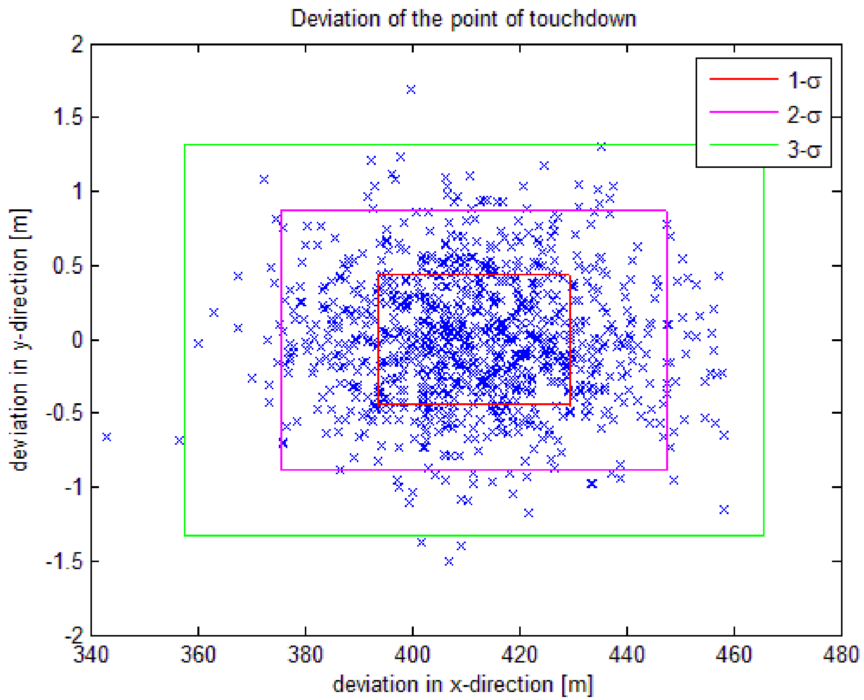


Modular approach:

1. Start deriving requirements using kinematic models
2. Enrich your model with aircraft specific data (weight and balance, actuators, bank angle limitations)
3. Enrich your model with aerodynamics, and subsystems dynamics as soon as aerodynamic data is available
4. Build 6-DOF model, trim and linearize the aircraft motion and use linear approximations or nonlinear system for further investigations

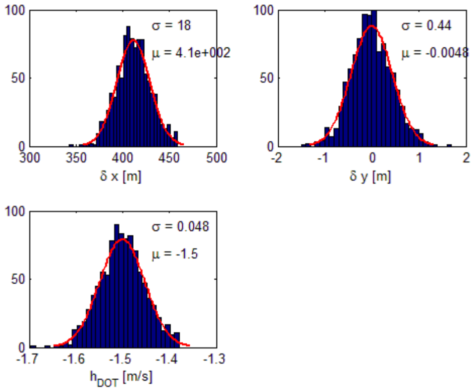
Probabilistic analyses

- Perturbation of initial conditions and system errors (e.g. position of flare initiation)
- Perturbation of closed-loop dynamics
- Overlapping of errors and simulation of resulting probabilities



Preliminary requirements determination

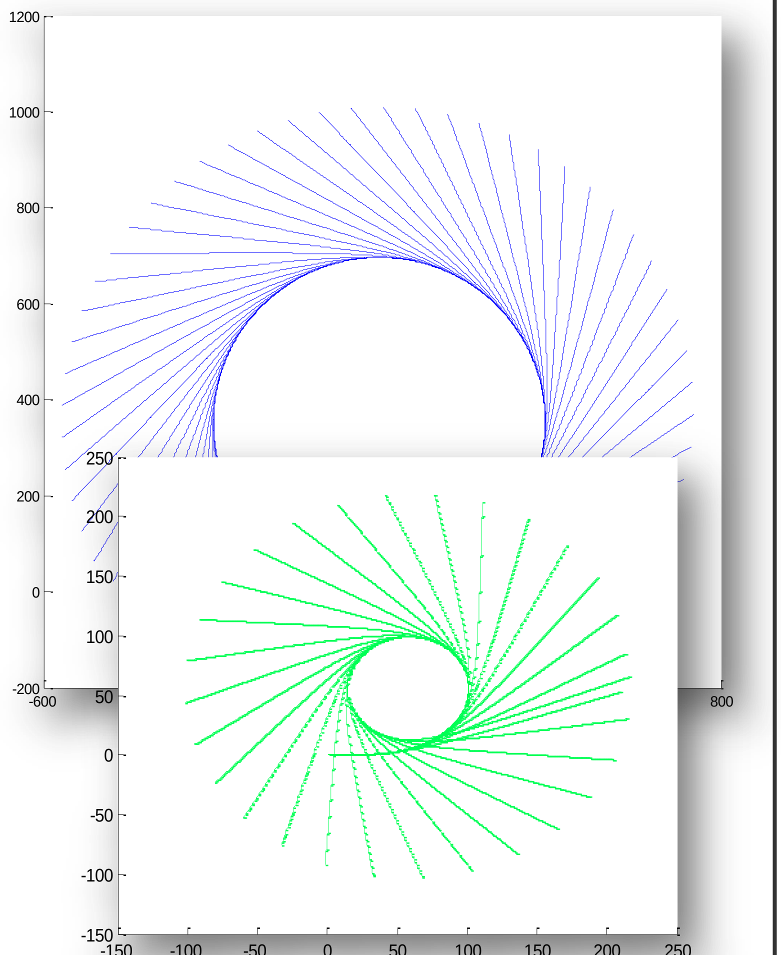
- Determination of touch-down point
- Determination of touch down velocity
- Influence of sensor errors on flown trajectory
- Sensor accuracy determination
- Specification of closed loop dynamics



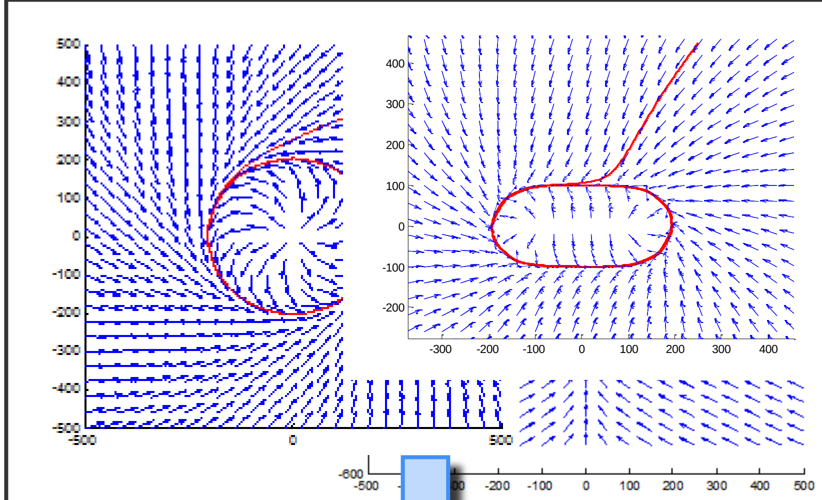
Making Visions Fly

Trajectory Specification with Augmented Simulation Models

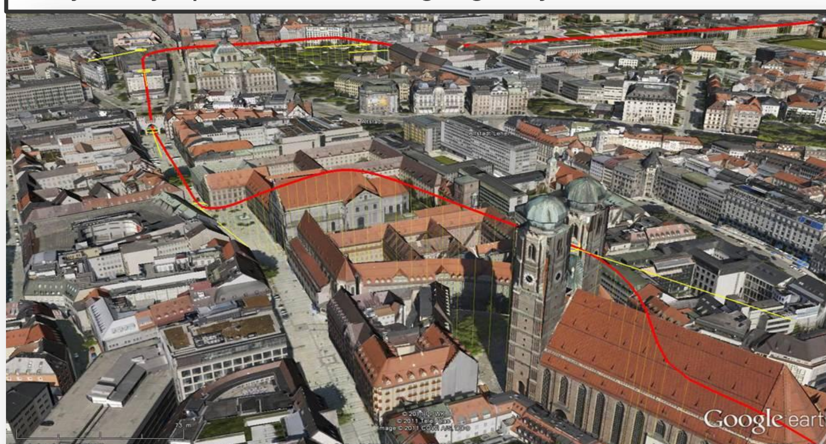
Specification of minimum waypoint distance for different velocities and actuator dynamics using kinematic models



Waypoint planning e.g. using vector fields



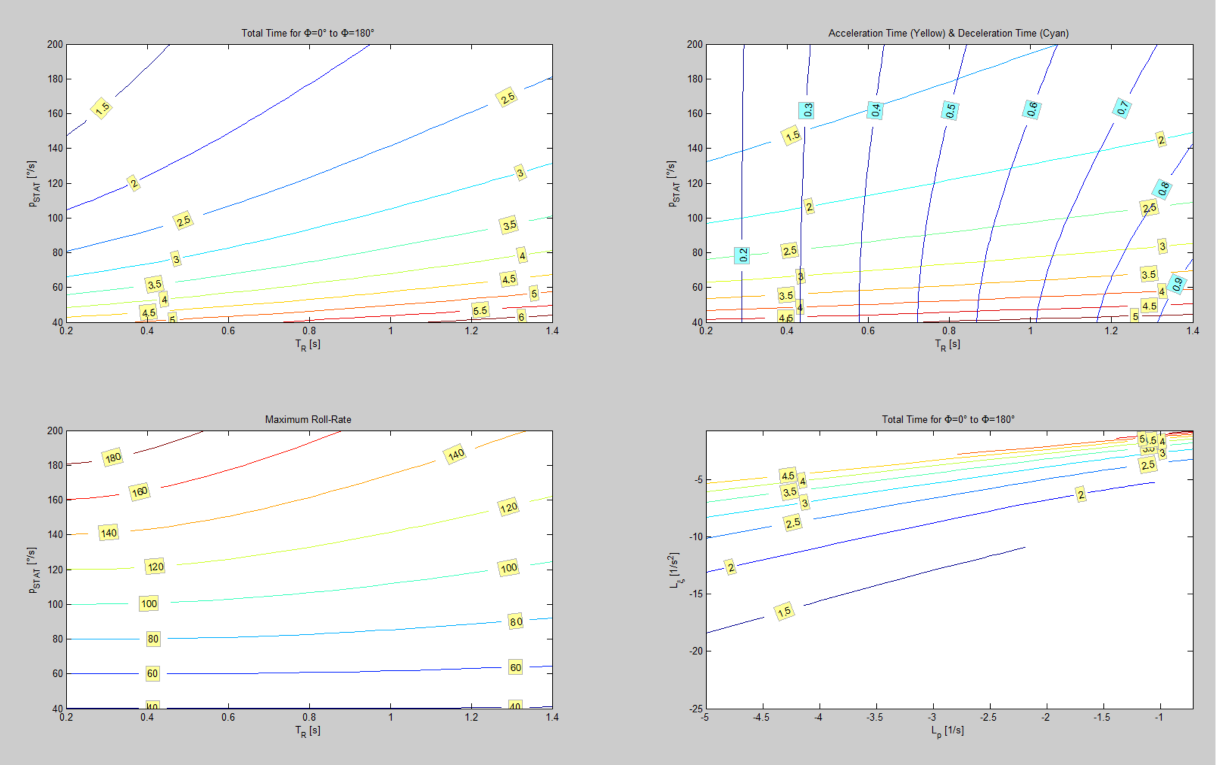
Trajectory specification using flight dynamics models



Simple linearized approximations of aircraft motion can be used for e.g.:

- Validation of performance requirements (Example: Roll to 180° within 2 seconds)
- Linear system $\dot{p} = L_p p + L_\xi \xi$

  $\dot{\Phi} = p$
- Results time constant for roll motion compliant with requirement



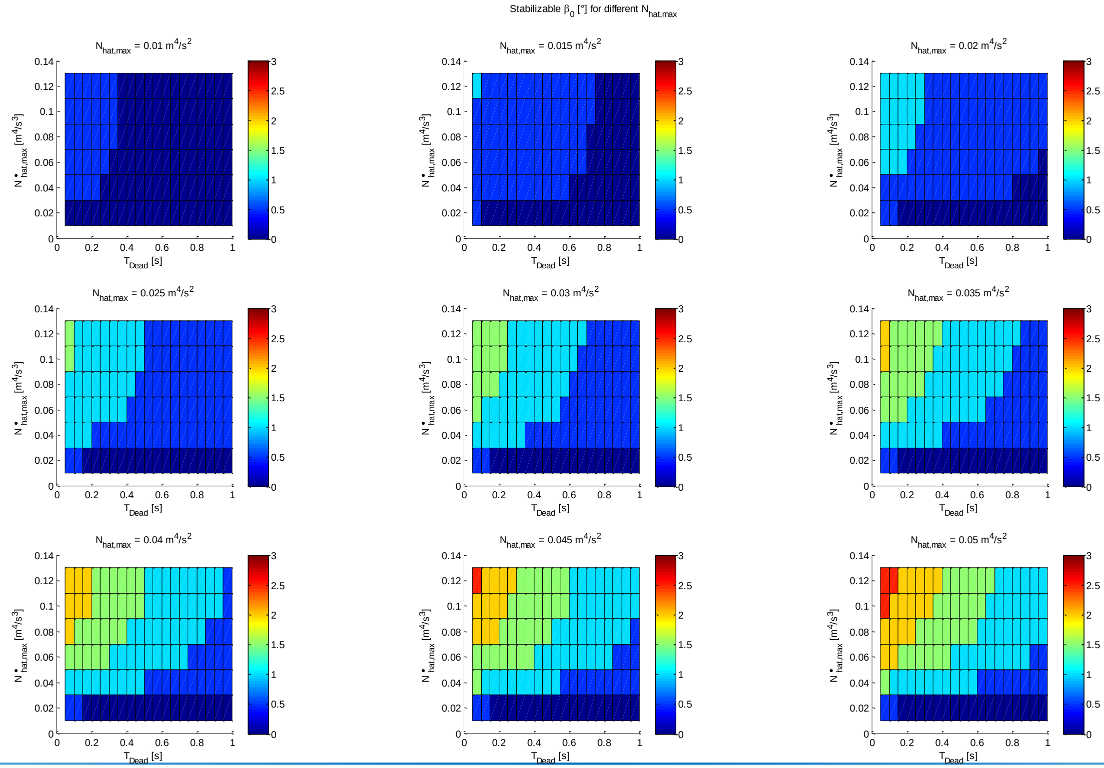
Simple linearized approximations of aircraft motion can be used for e.g.:

Derivation of actuator parameters and aerodynamic effectors for stabilization of unstable yaw motion

- Linear system $\dot{r} = N_r r + N_\beta \beta + N_\zeta \zeta$

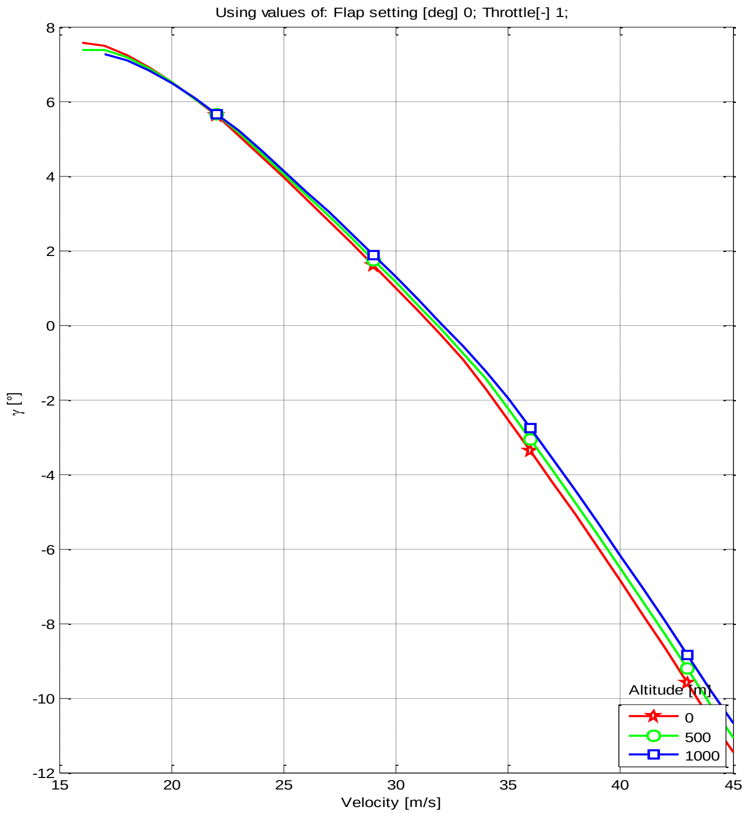
  $\dot{\beta} = r$

- Results $N_{\zeta_{MAX}}, \dot{N}_{\zeta_{MAX}}, \beta_{0_{MAX}}, T_{delay}$ (actuator)

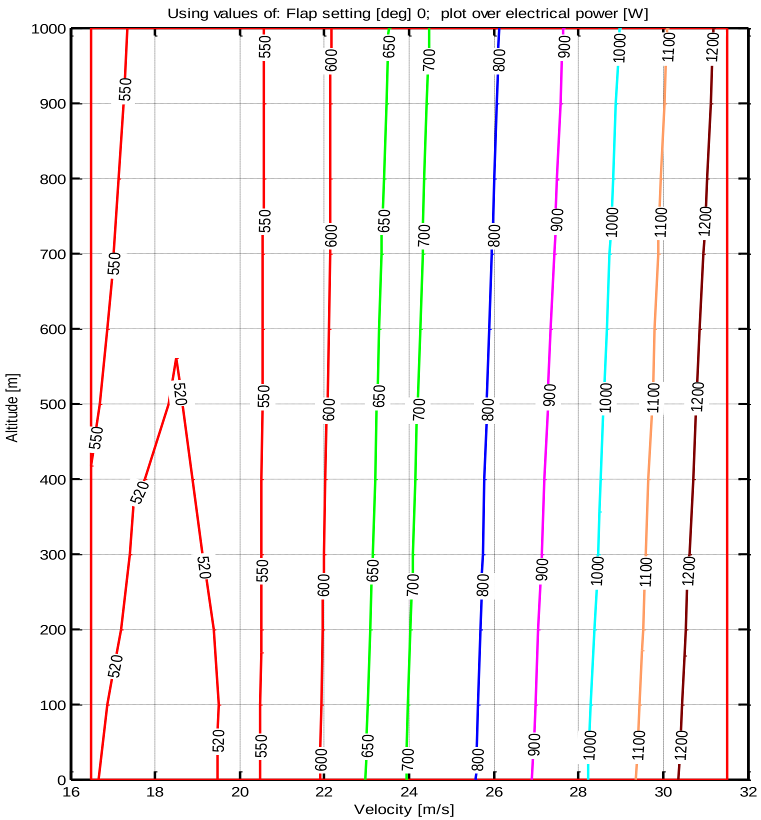


Trim curves for different flight conditions are useful for determination of **flight envelope**, **envelope limitations** and **optimum flight conditions**

Climbing Flight @ const throttle:
Plot of γ over velocity and altitudes



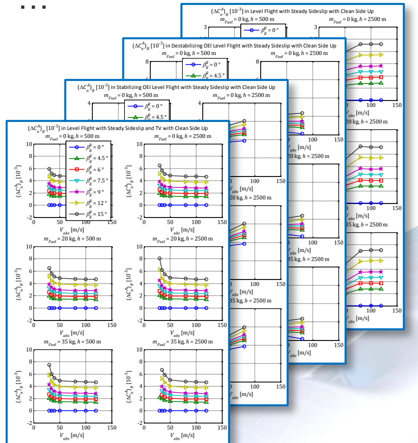
Level Flight: Envelope of constant power demand



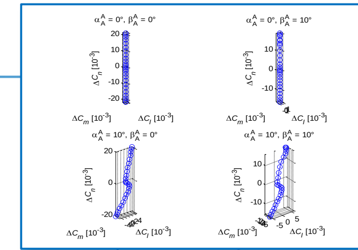
Making Visions Fly
Functional Controls Layout & Assessment

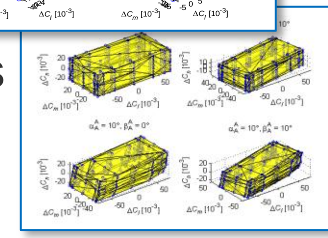
- High-Level Requirements:
  - E.g., it should be possible to take-off and land with up to 10 kts cross wind
  - …

Trim curve and performance analysis for a set of generic controls



- Attainable Moment Subsets (AMS)





Controls Concept

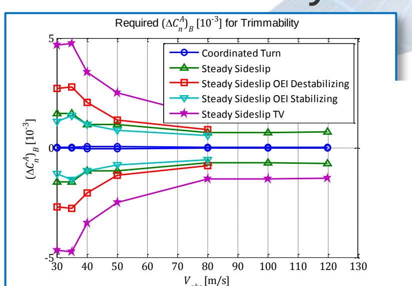
Control Allocation

Trim curve & performance analysis, stabilization assessment

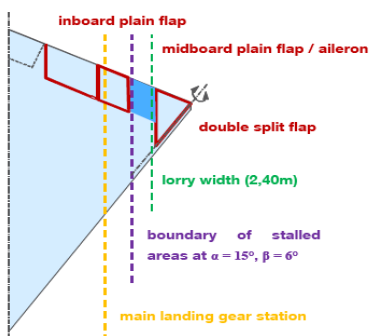
Controls Re-Design

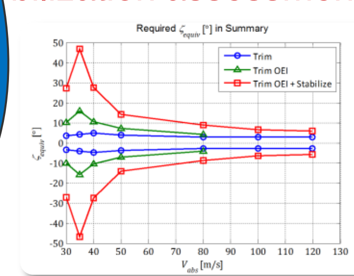
Controls Re-Design

- Control Authority Requirements

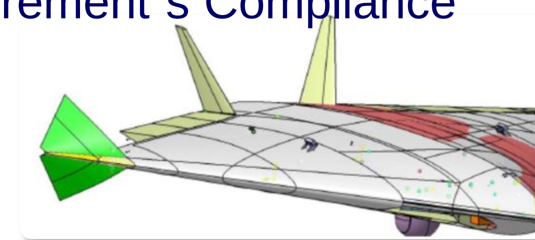


Controls Layout





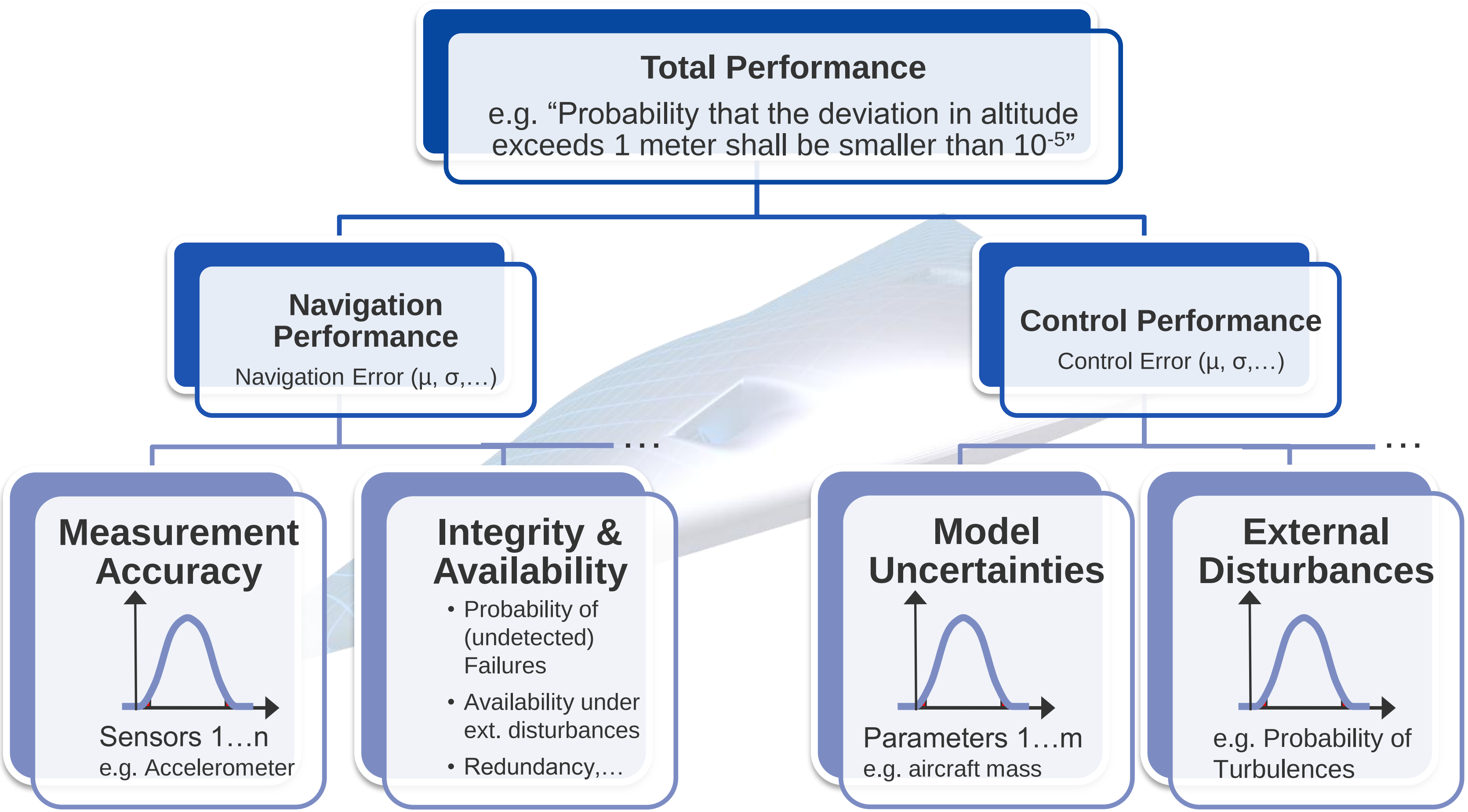
- Controls Demand & Requirement´s Compliance
  - One main effector for each axis
  - Split/Schedules …



Total System Capability Approach: Idea & Methodology

- Overall system is required to deliver a certain performance
- Behavior of integrated system is driven by all contributing elements
  - ⇨ e.g. Sensors, Actuators, Computers, Disturbances,...
- Instead of allocating hard tolerance budgets to the individual disciplines
  - ⇨ Consideration of the overall system simultaneously
- Certain Performance required to provide a Safe System / Operation
  - ⇨ Using quantitative analyses, probability of undesired Failure Conditions can be calculated
  - ⇨ The more severe a Failure Condition is, the lower the risk for its occurrence is required

Making Visions Fly
Total System Capability Approach: Decomposition Tree

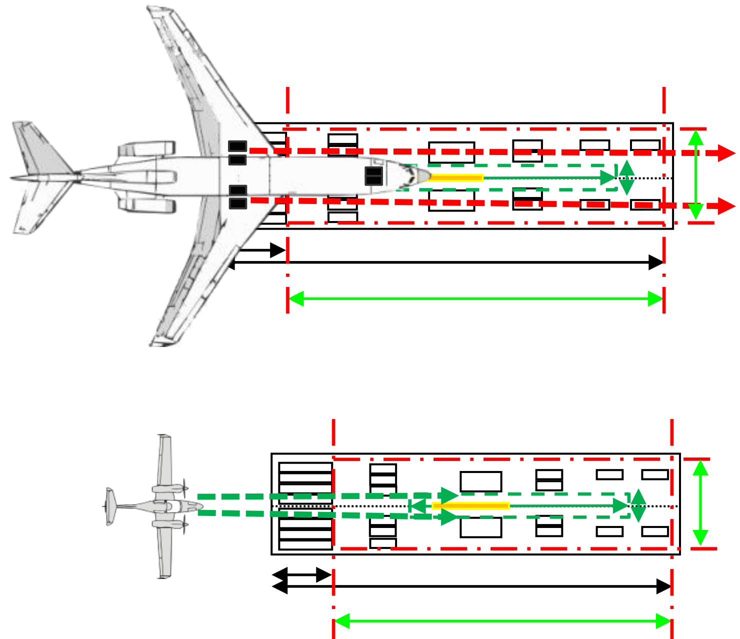


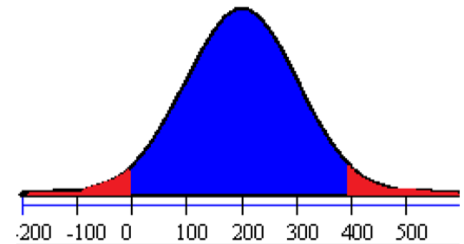
Making Visions Fly

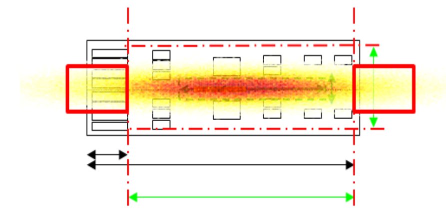
Total System Capability Approach for Image Aided Landing

- Prediction example for longitudinal touchdown point
- Based on known distributions of relevant variables the numerical probability of a runway overrun can be calculated

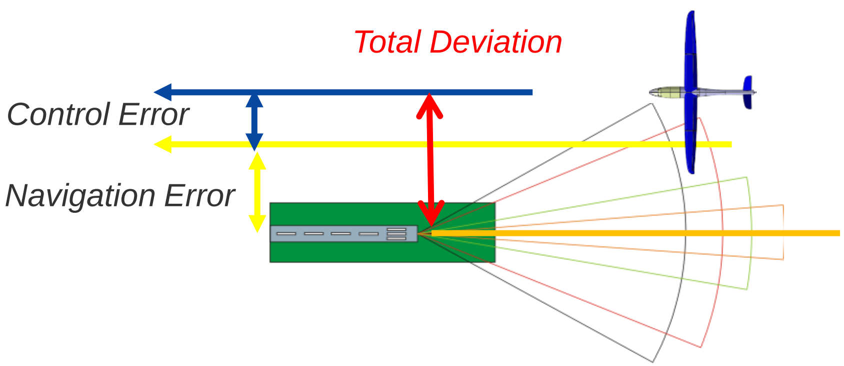
Narrow runway, Wide wheel track







Wide runway, Narrow wheel track



- Formulate requirements
  - with respect to total deviation
  - related to actual situation & environment
- Define safety driven alert levels to meet safety goals
- Predict system performance statistics online
- Compare performance prediction to alert level
- System only useful if resulting availability is high

How is the system influenced by changes of external parameters?

⇨ Environmental conditions
  ⇨ Static atmosphere: temperature, pressure, density
  ⇨ Dynamic atmosphere: wind, gust, turbulence
  ⇨ Precipitation (rain, snow, hail, icing)
⇨ System effects not accounted for in modeling
  ⇨ Tether artefacts (vibration, stiffness, expansion etc.)
  ⇨ Higher order dynamics
  ⇨ …
⇨ Foreign objects (bird strike, …)

And how can those influences be considered with respect to their impact on the Availability as the global optimization parameter?

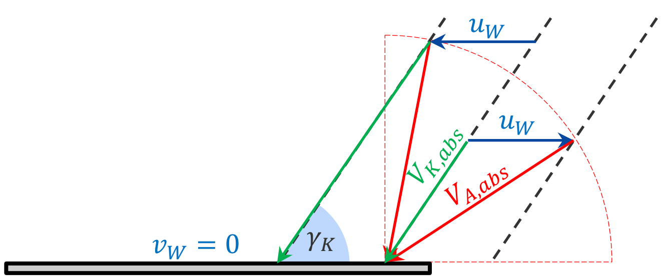
⇨ **Sensitivity analysis**

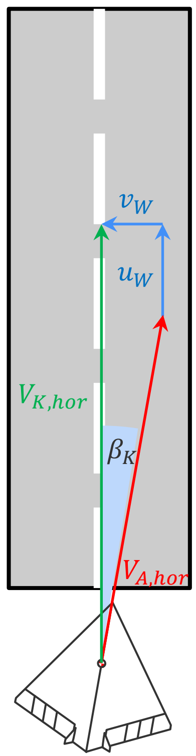
Crab Angles and Linear Impulse on Landing Gear during Landing:

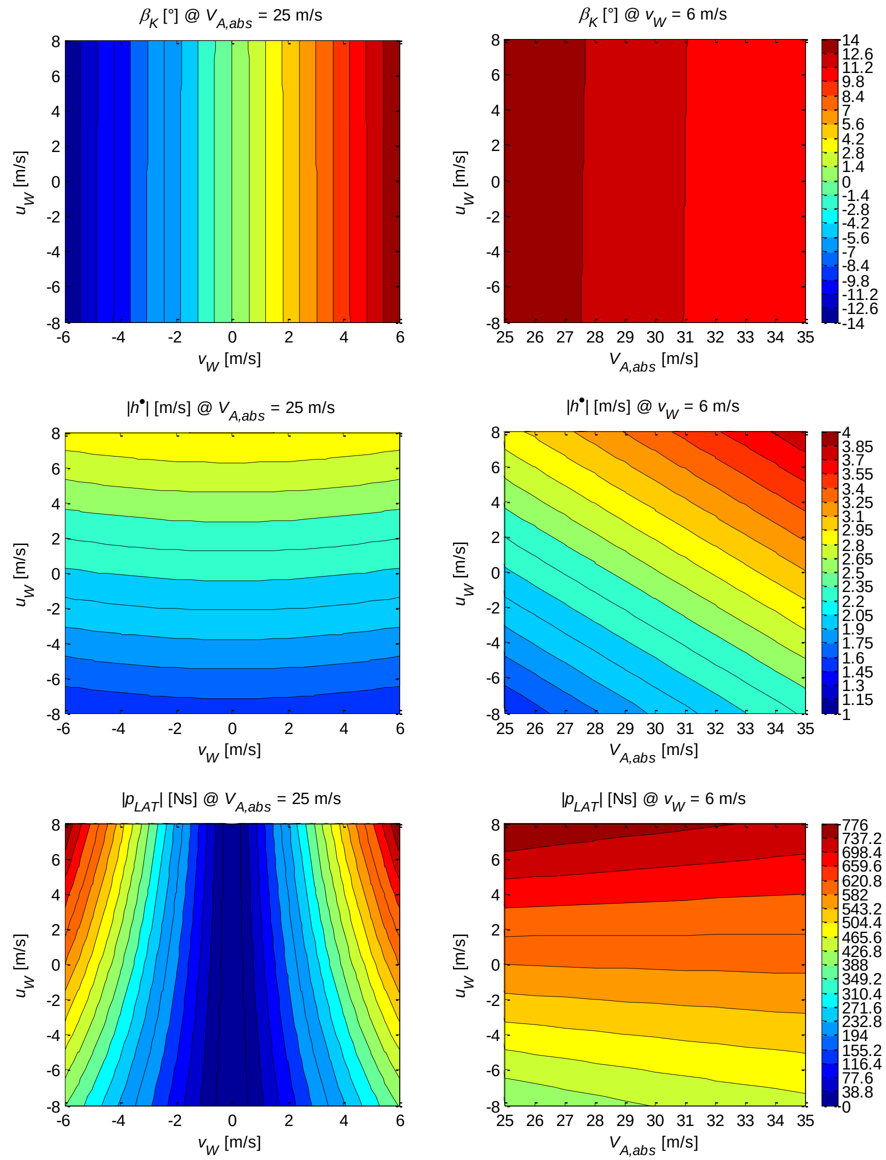
- Final approach with
  - mass $m = 100\ \mathrm{kg}$
  - constant path slope -9% (TLR) ⇨ $\gamma_K \approx 5°$
  - constant $V_{A,abs}$

  $V_{K,abs}$ depends on wind conditions
- Head / tail wind up to 15 kts (TLR) ⇨ $u_W \in [-7.7, 7.7]\ m/s$
- Cross wind up to 10 kts (TLR) ⇨ $v_W \in [-5.1, 5.1]\ m/s$

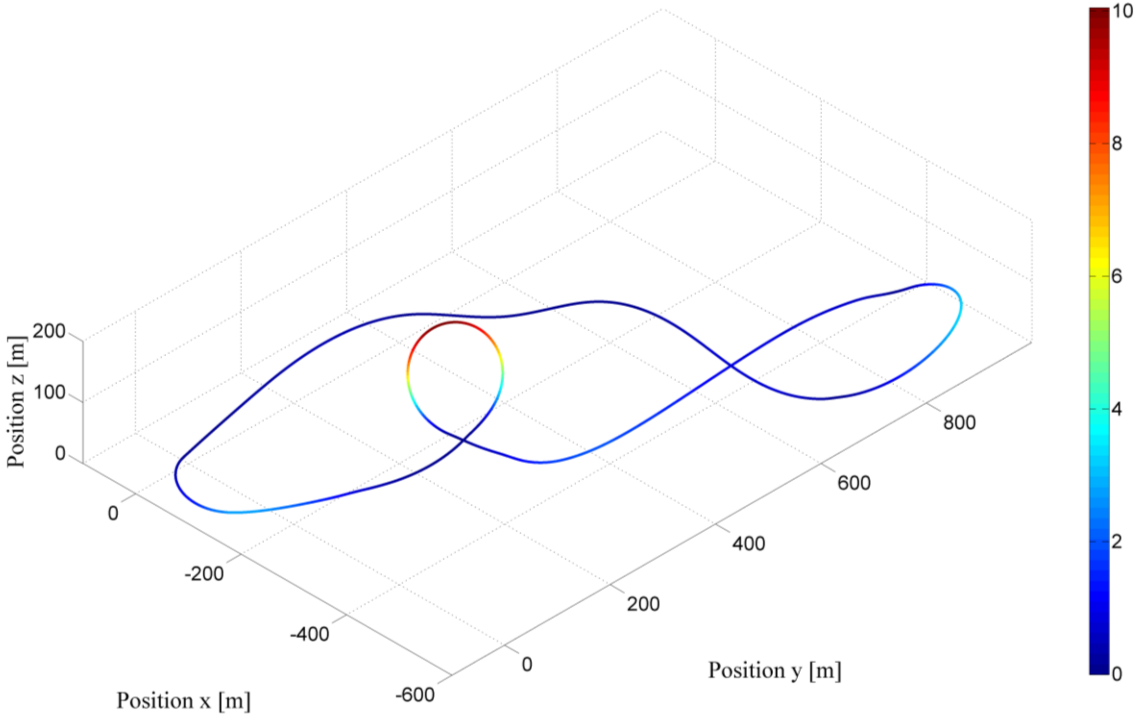
⇨ Crab angle β_K, sink rate $\dot{h}$ and lateral linear impulse p_{LAT} w.r.t. $V_{A,abs}$, u_W and v_W







Sensitivity analysis of the nominal trajectory against disturbances



⇨ Sensitivity measure:

$$\frac{ds^i}{dp}(p_0) = \sqrt{\left(\frac{dx^i}{dp}(p_0)\right)^2 + \left(\frac{dy^i}{dp}(p_0)\right)^2 + \left(\frac{dz^i}{dp}(p_0)\right)^2}$$

⇨ Displacement of optimal trajectory in respect to wind speed!

From functional considerations to the **Storybook of Flight**

– Operational phases and their requirements

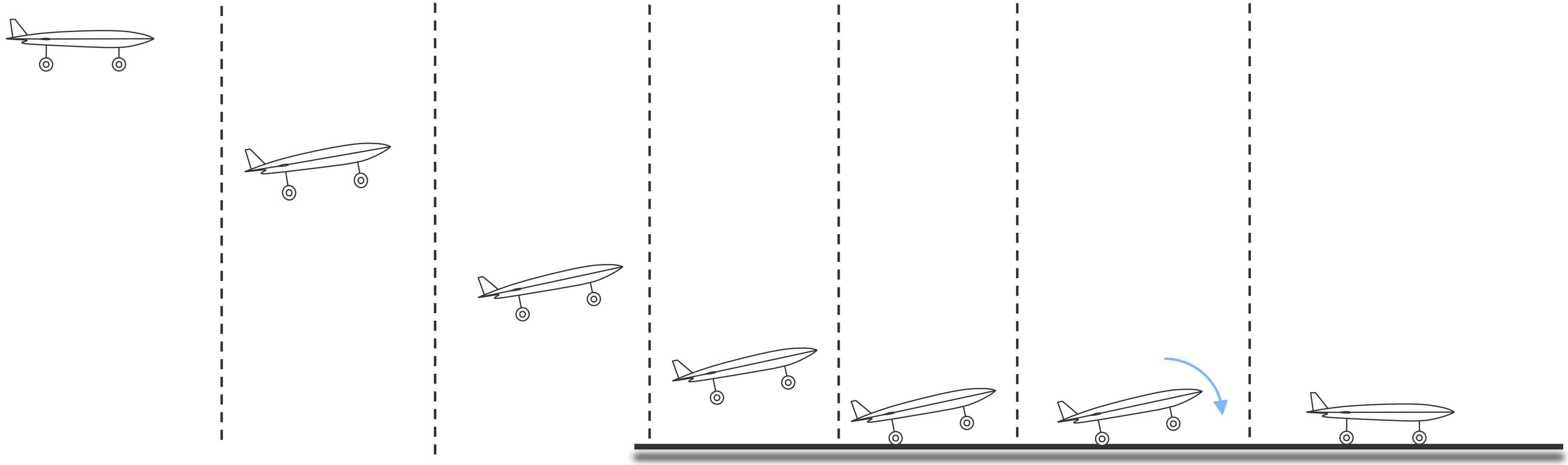
Identification of

- Different flight phases of the system
- Their boundary conditions
- Initialization and initial values (especially for simulation and computer based optimization)
- Entry and exit criteria
- Phase transition criteria
- Non-Nominal flight phases:
  - ⇨ Failure recovery
  - ⇨ Emergency situations
  - ⇨ Degraded and alternate operational modes

Every flight phase needs its Requirements!

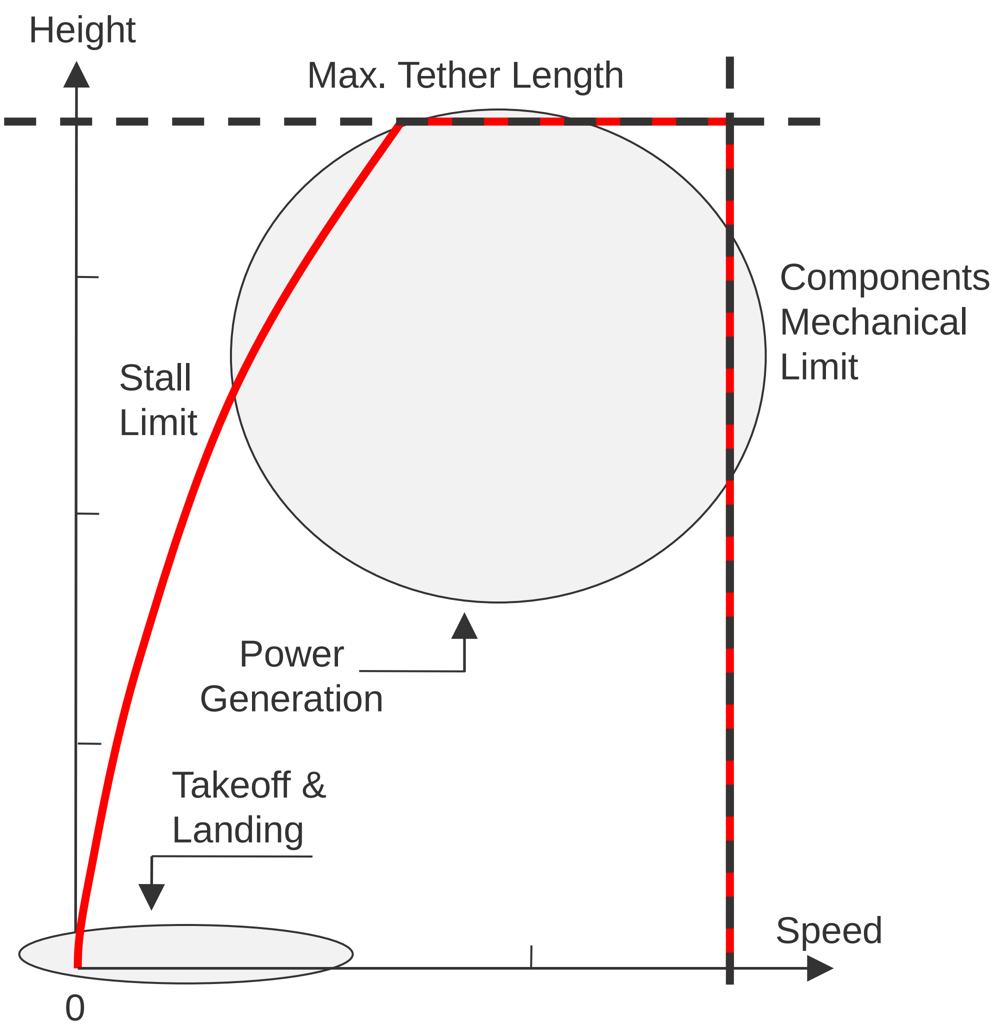
Functions and Moding for Nominal Landing Maneuver (Example)

Phase	intermediate	final		decrab	touchdown	derotation	deceleration
Lateral	standard precision trajectory control	high precision trajectory control	high precision trajectory control	heading by yaw, bank angle control	heading by yaw	heading by yaw	heading by NWS
Vertical	standard precision trajectory control	high precision trajectory control	vertical speed	vertical speed	vertical speed	nose down command	nose down command
Speed	standard precision trajectory control	high precision trajectory control	speed by throttle	idle thrust	idle thrust	idle thrust	idle thrust
Systems	automatic gear deployment						brakes command



Identification of Potential Flight Phase dependent Requirements for HAWE Systems

Possible Operational Flight Envelope of a High Altitude Wind Energy System:



Fixed Wing HAWE System:

Phases:

- Start / Launch
- Acceleration
- Transition
- Power Generation Phase
- Transition and Deceleration
- Hover
- Reel In
- Dock / Locking

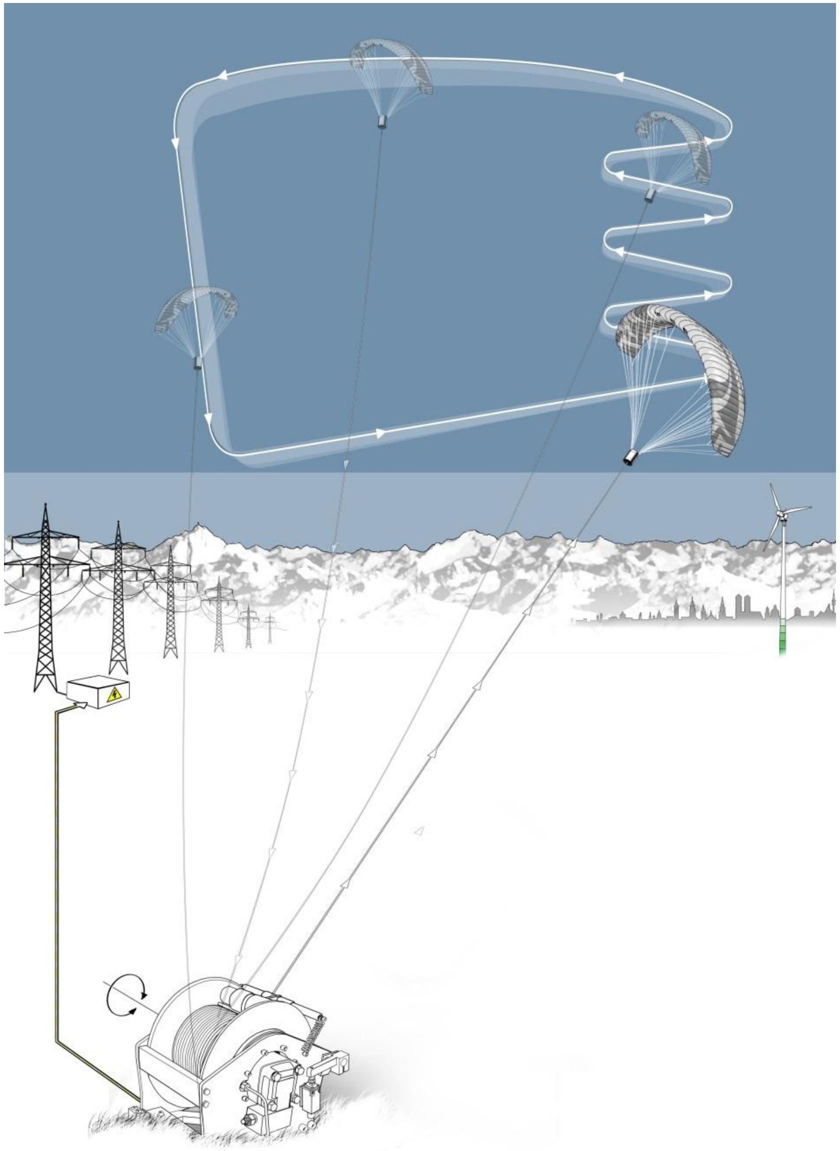
Kite Based HAWE System:

Phases:

- Start / Launch
- Acceleration
- Transition
- Power Generation Phase
- Transition to Hover
- Depower / Folding
- Reel In
- Transition and Deceleration
- Hover
- Reel In
- Dock / Locking

Pumping Cycle

Making Visions Fly
Flight Phase dependent Requirements for HAWE Systems



Exemplary requirements for kite based systems:

Phase	Lateral	Vertical	Speed	Systems
Start / Launch				
Acceleration				
Transition				
Power Generation Phase				
Transition to Hover				
Depower / Folding				
Reel In				
Transition and Deceleration				
Hover				
Reel In				
Dock / Locking				

?

Requirements Engineering

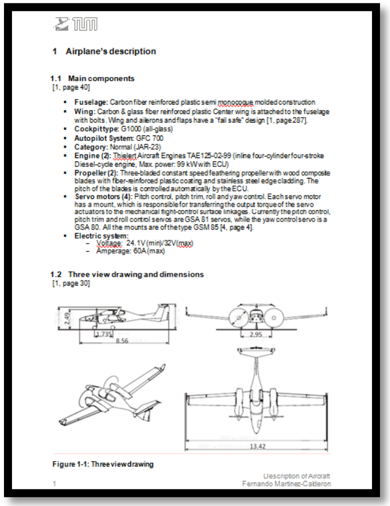
- Top-Down process: formulation and formalisation of High-Level requirements down to Low-Level software and hardware requirements
- Requirement-Standards:
  - ⇨ Verifikation
  - ⇨ Traceability
  - ⇨ Testability
  - ⇨ Reusability

or:

How to make sure that no requirement is left open and the system does what it shall do…

Templates and Guidelines for Requirements Analysis:

System Environment Description


1 Airplane's description

1.1 Main components

1.2 Three view drawing and dimensions

Figure 1-1: Three view drawing

Functional Description

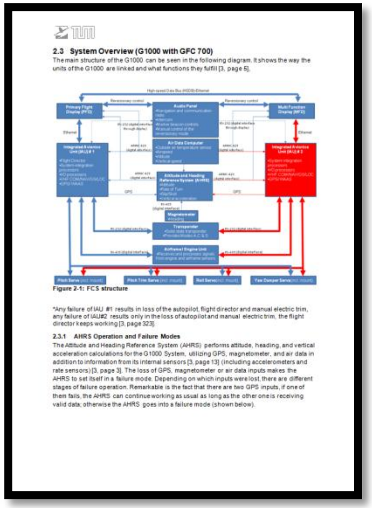
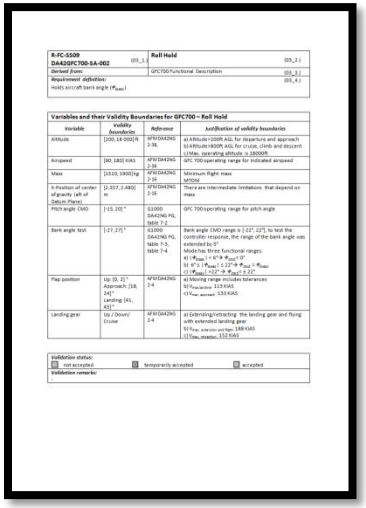

2.3 System Overview (G1000 with GFC 700)

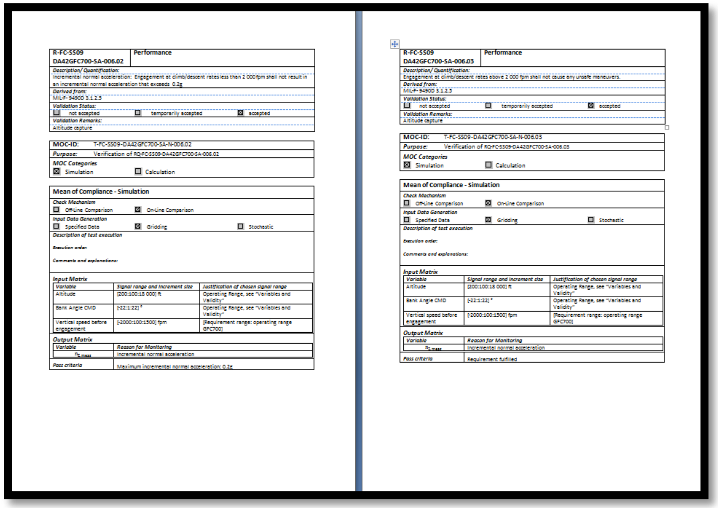
Figure 2-1: FCS structure

2.3.1 AHRS Operation and Failure Modes

High-Level Requirement



Low-Level Requirement



Formulation of High-Level Requirements

Requirement ID

Requirement Name

R-FC-WS09
DA42AP-001 (03_1.)

Altitude Select & Hold (03_2.)

Derived From:	Functional Description (03_3.)

Requirement Formulation →

Altitude Capture: When the difference between aircraft altitude and selected altitude is within a later defined boundary the mode changes from Altitude Acquire (AA) to Altitude Hold (AH).

Requirement Definition: (03_4.)

An Altitude Select & Hold functionality shall be implemented. It shall consist of three modes:

Altitude Acquire: The Altitude Acquire functionality takes the desired altitude and approaches the reference altitude by climbing with a constant rate.

Altitude Capture: When the difference between aircraft altitude and selected altitude is within a later defined boundary the mode changes from Altitude Acquire (AA) to Altitude Hold (AH).

Altitude Hold: This functio… maneuver. The Altitude H…

Bou…

Variables and their Validity Boundaries for Altitude Select and Hold

Variable	*Validity Boundaries*	*Reference*	*Justification of Validity Boundaries*
Altitude	[200, 18 000] ft	3, page 57	a) Altitude>200ft for departure and climb b) Max. demonstrated altitude is 18000ft
Airspeed	[90, 180] KIAS	3, page 57	operation range desired by the customer
Mass	[1250, 1785] kg	3, page 48	MTOM = $Mass_{max}$ =1785
X-Position of center of gravity	[2.35, 2.49] m	3, page 49	There are Intermediate limitations that depend on mass
Bank angle	[-30, 30] °	MIL 9490D	The accuracy defined by MIL 9490D depends on the actual bank angle
Flap position	Up: [0, 2] ° Approach: [18, 24] ° Landing: [41, 45] °	4, page 2	a) Moving range includes tolerances b) $V_{max,landing}$: 113 KIAS c) V… : 133 KIAS

Validation Status →

Validation Status:

☐ not accepted ☒ temporarily accepted ☐ accepted

Validation Remarks:

None

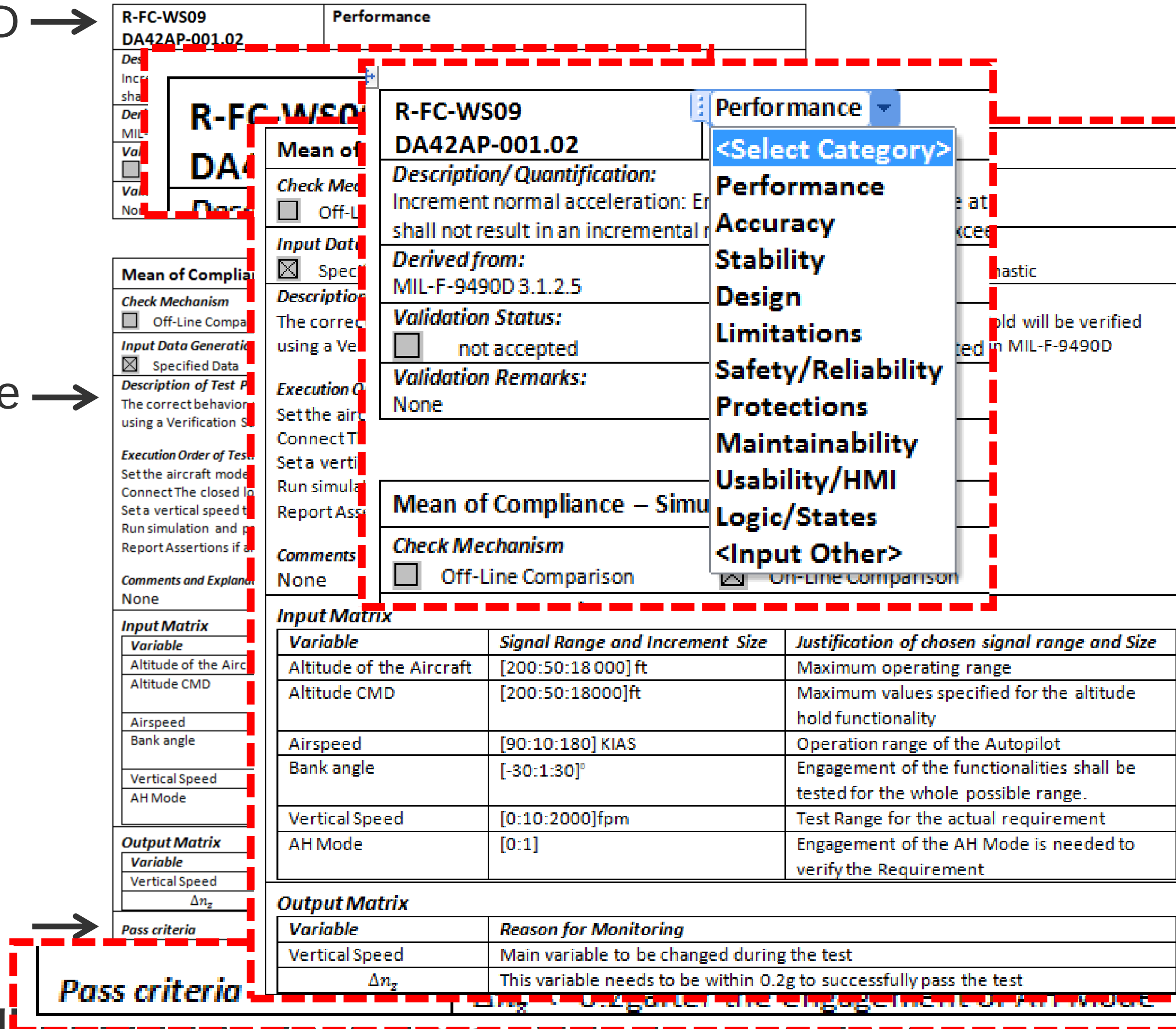
Formulation of Low-Level Requirements

Category

Low-Level Requirement ID

Means of Compliance

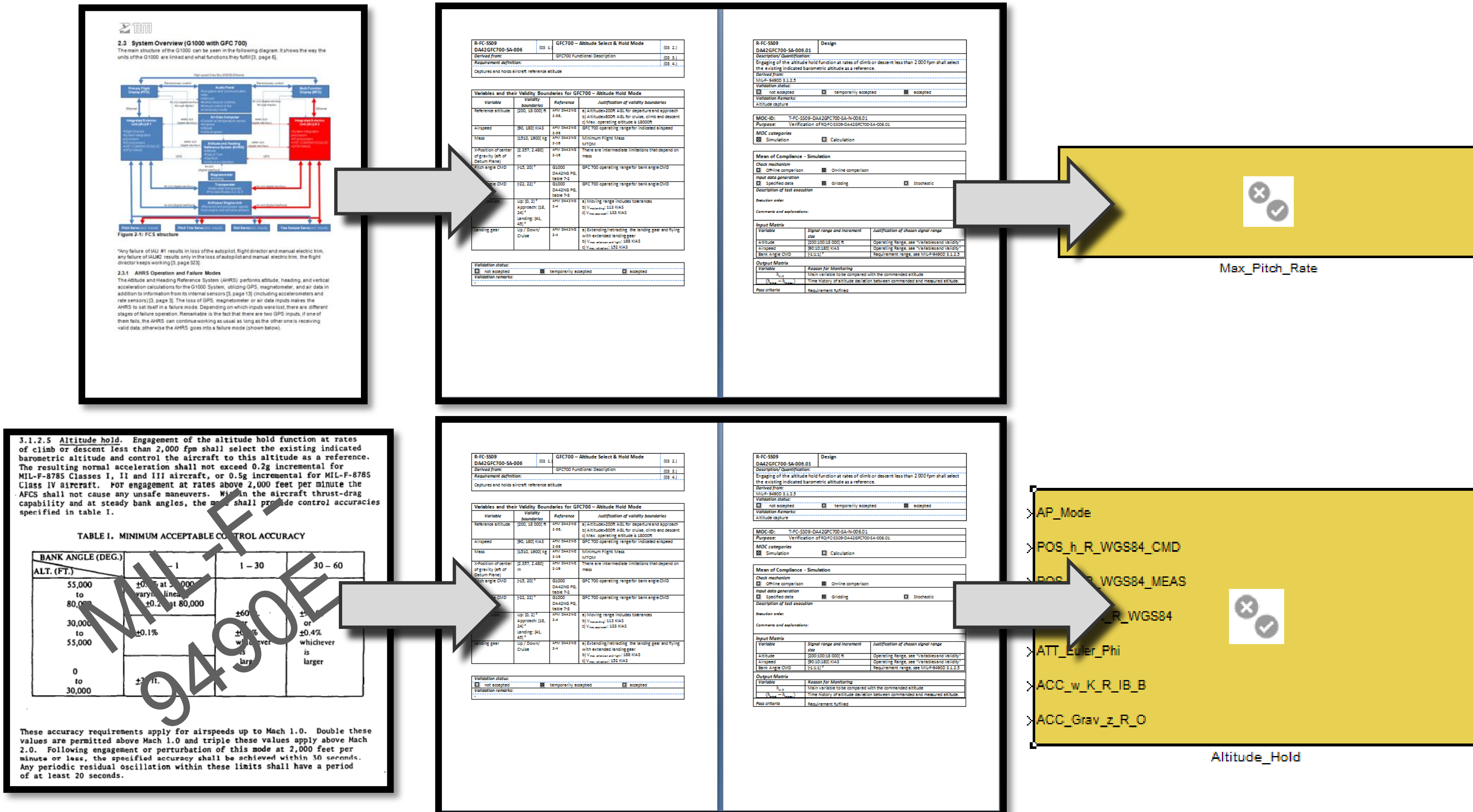
Pass Criteria



Intention: To ensure q

Requirements are captured in templates and translated into formal expressions

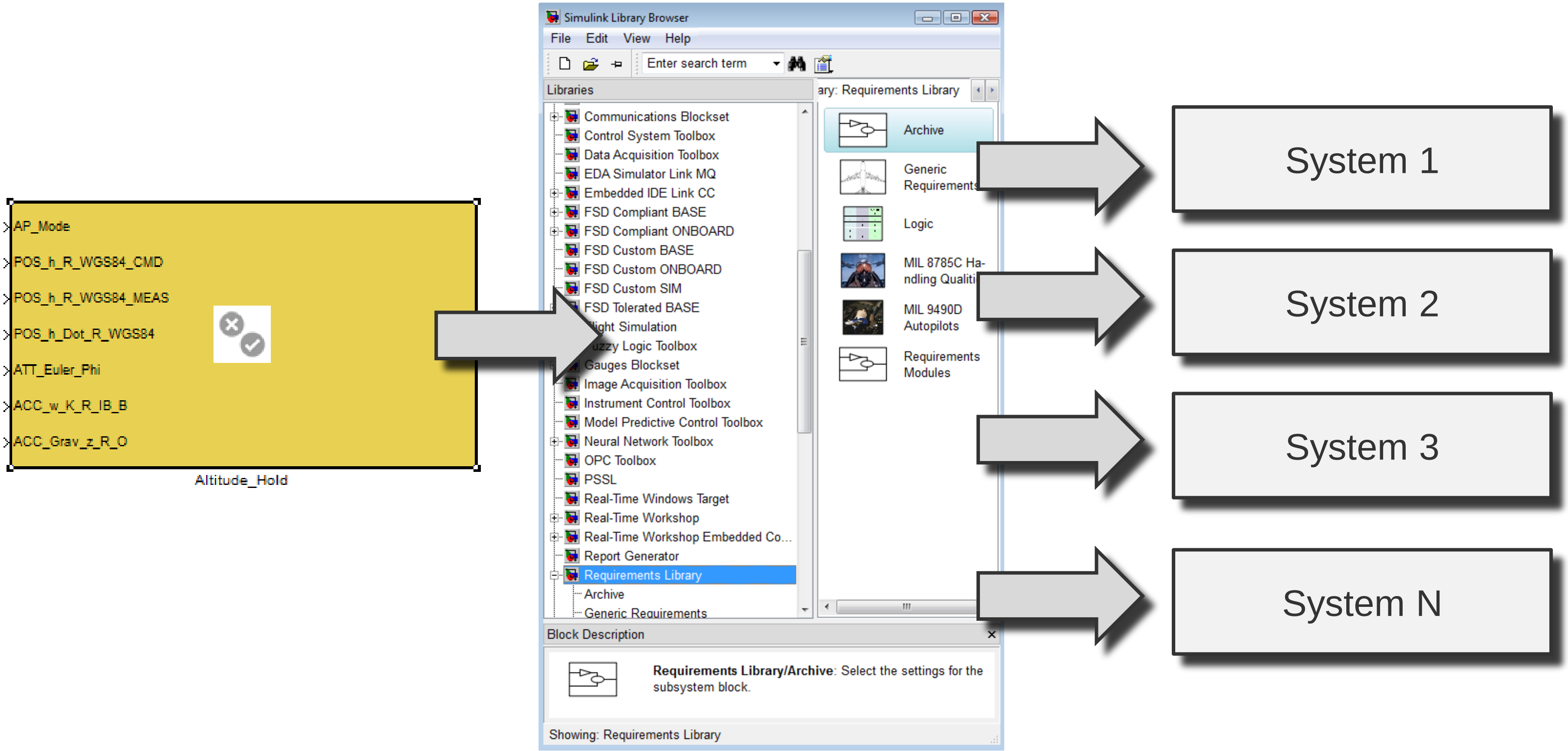
⇨ Verification of functionality during runtime



Making Visions Fly

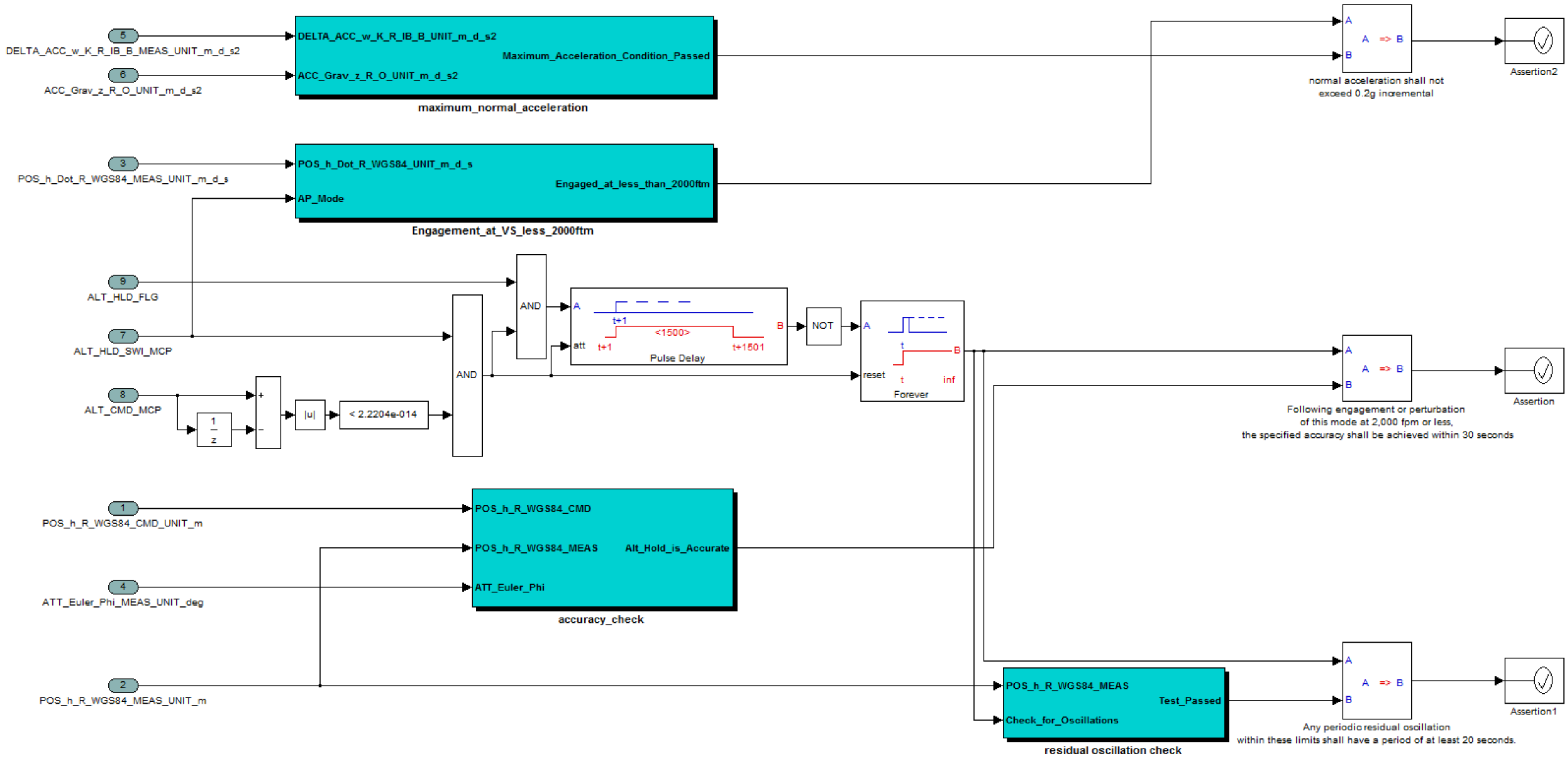
Collection of requirements in libraries for the purpose of reuse

Recurring requirements (like requirements to autopilots) are collected in libraries for the purpose of reuse



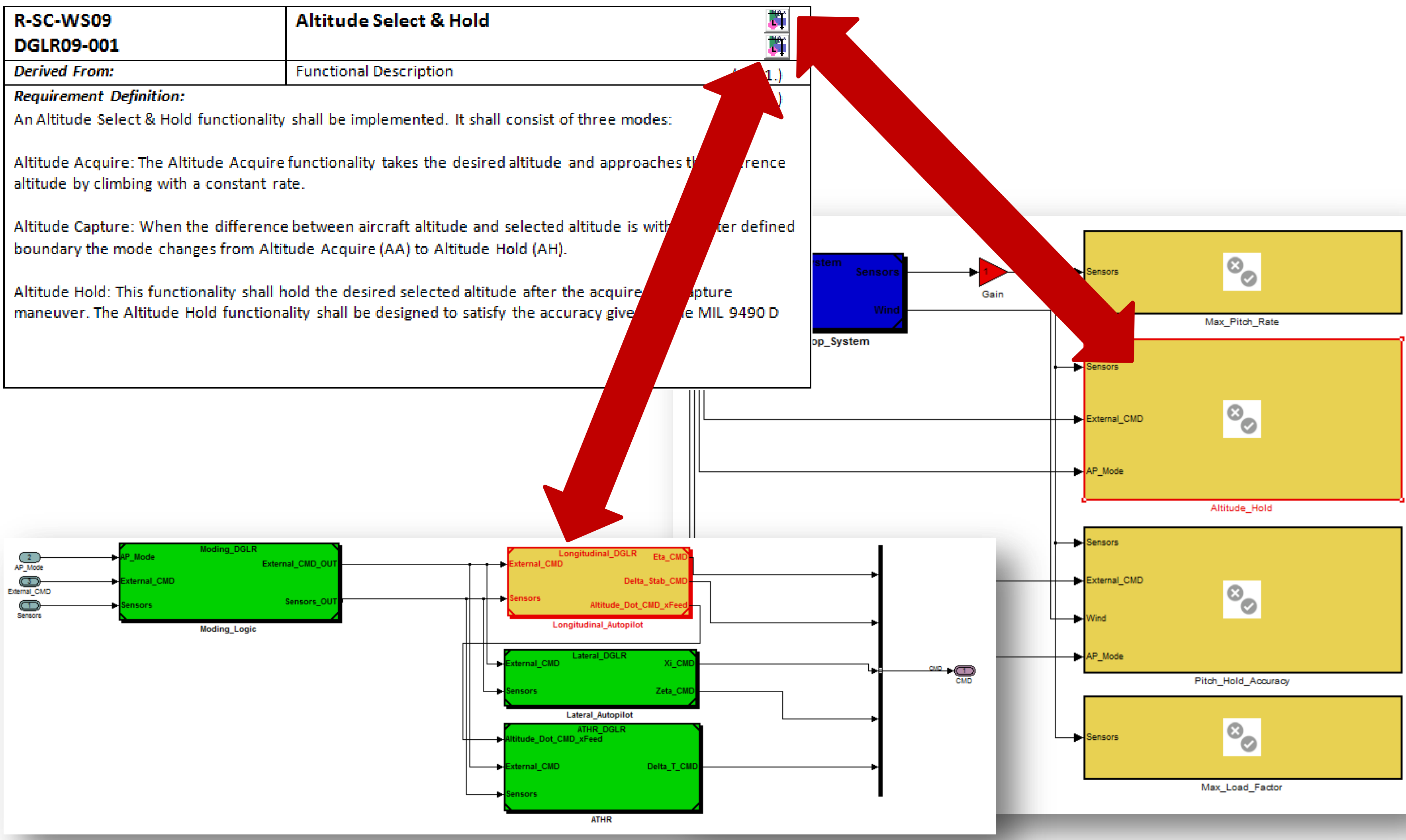
⇨ Reduction of time and effort as well as better comparability of systems!

Making Visions Fly
Complex Requirement



Making Visions Fly

Traceability: Requirement to model / model to requirement



R-SC-WS09 DGLR09-001	Altitude Select & Hold
Derived From:	Functional Description 1.)

Requirement Definition:

An Altitude Select & Hold functionality shall be implemented. It shall consist of three modes:

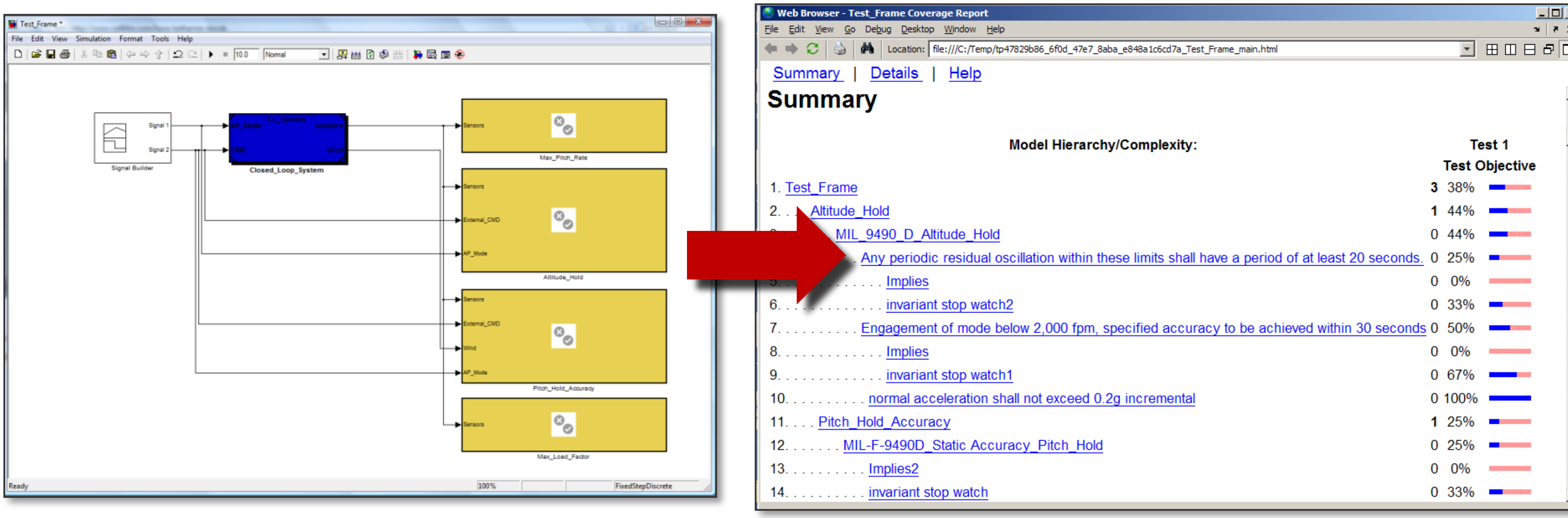
Altitude Acquire: The Altitude Acquire functionality takes the desired altitude and approaches th … rence altitude by climbing with a constant rate.

Altitude Capture: When the difference between aircraft altitude and selected altitude is with … ter defined boundary the mode changes from Altitude Acquire (AA) to Altitude Hold (AH).

Altitude Hold: This functionality shall hold the desired selected altitude after the acquire … pture maneuver. The Altitude Hold functionality shall be designed to satisfy the accuracy give … e MIL 9490 D

Making Visions Fly

Automatic test reports and coverage statement

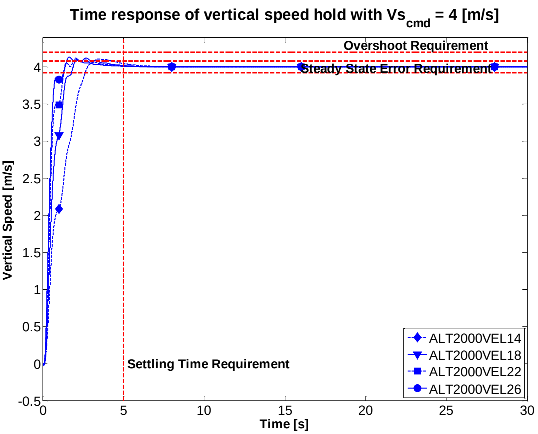


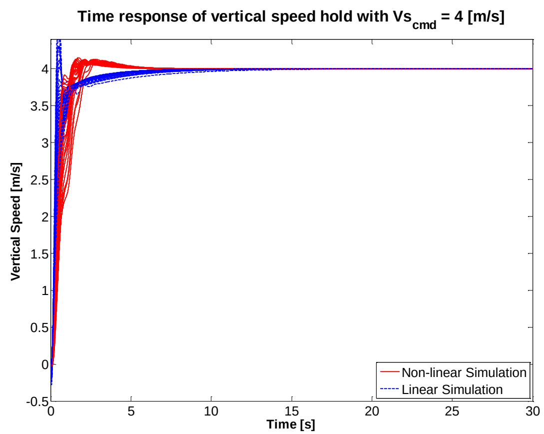
- Formalized requirements can be enriched with test objectives and assumptions which will be automatically checked during test execution
- The evaluation of test objectives and the report genetation are performed automatically

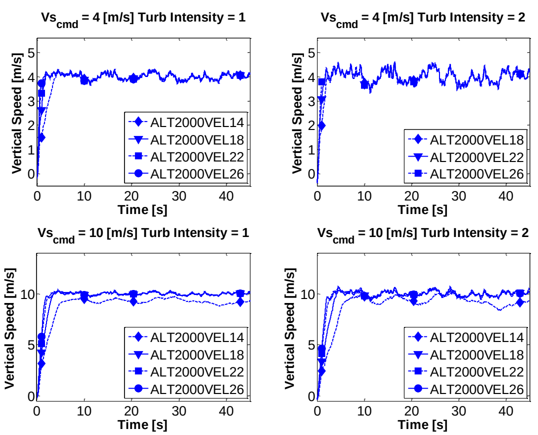
Offline verification with simulation results

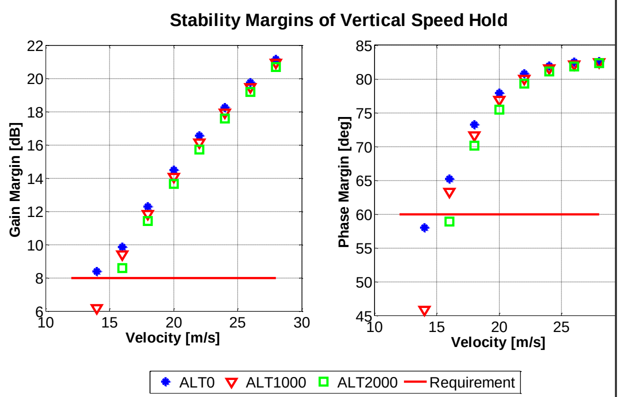
=> Standardization & Automation

Large number of tests must be managed

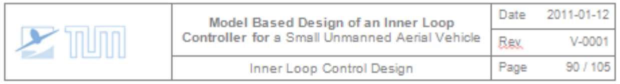








Template for results documentation



	Model Based Design of an Inner Loop Controller for a Small Unmanned Aerial Vehicle	Date	2011-01-12
		Rev	V-0001
	Inner Loop Control Design	Page	90 / 105

4.3.1.5 T-DA-FCS-03.1

Requirement Name:	Gain Phase Margin	4–13
Requirement ID	R-DA_FCS_03, R-DA_FCS_03.1	4–14
Description of Requirement Compliance Procedure		4–15

Compliance is shown by means of frequency response Bode and Nichols plots for the different control loops. The plots are generated at different velocities and altitudes along the operation flight envelope.

Vel	[15,20,25,30]
Alt	[0,3000]

The smallest gain and phase margin is presented.

Roll rate command loop:

Min. Gain Margin	14.9	[dB]
Min Phase Margin	-180	[deg]

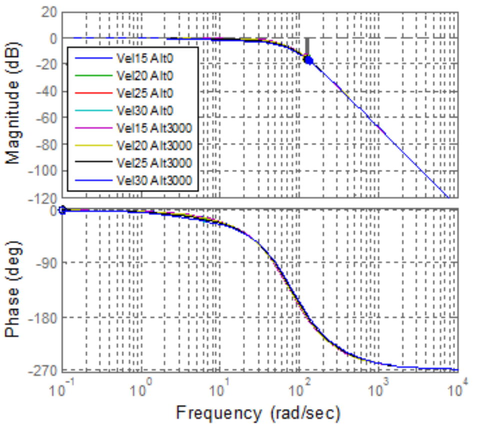


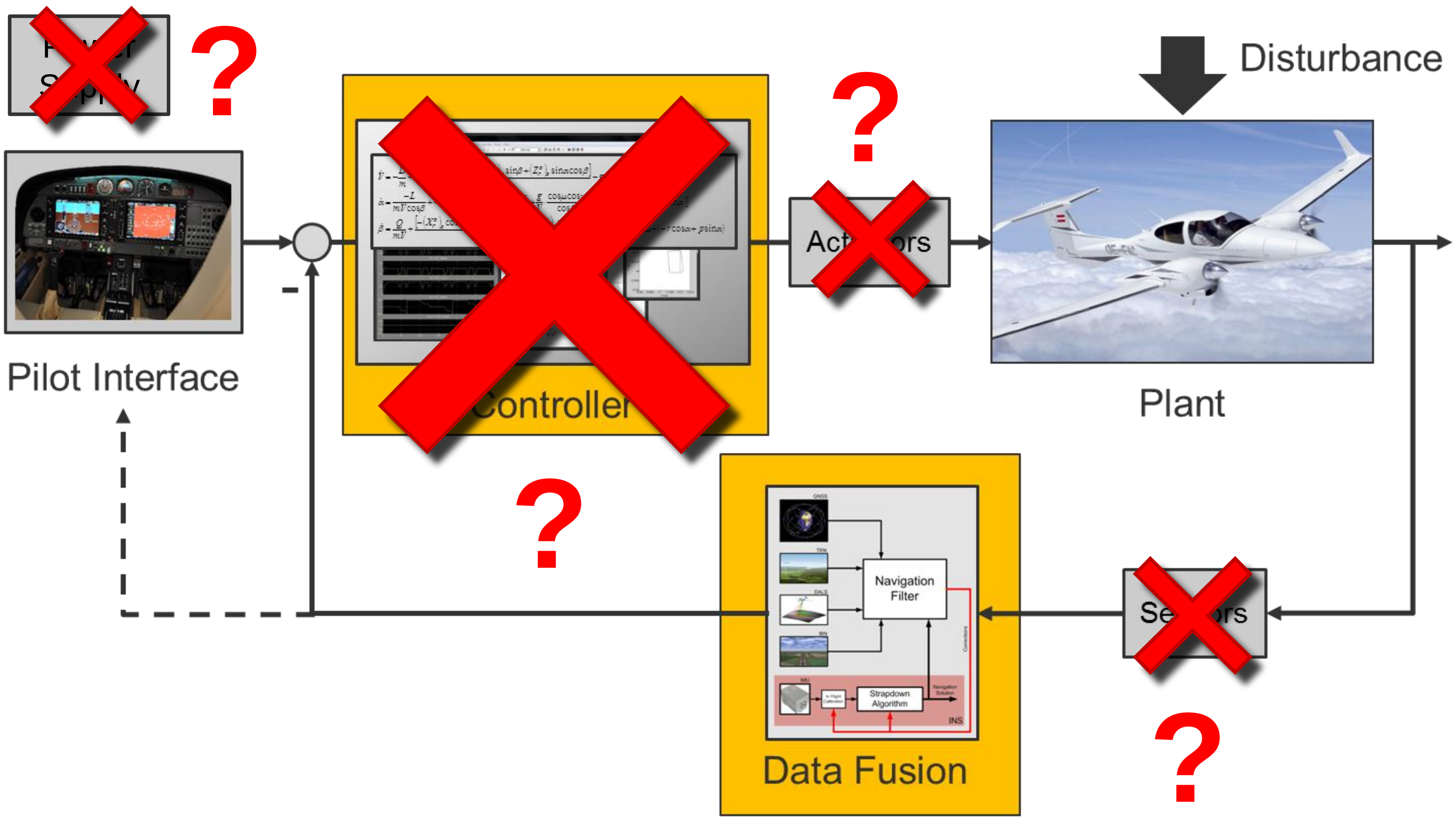
Figure 4.45: Bode Plot p_{cmd} to p

The Safety Assessment Process aims at answering the following questions:

- What could go wrong in the system?
- What are the consequences? How severe are they?
- How safe does the system need to be?
- Can the proposed system design be expected to be as safe as it should be?
- Is the actually implemented system design as safe as it should be?
- Are assumptions made during the system design analysis actually valid?
- Can we trust our system to be as safe as we want it to be?

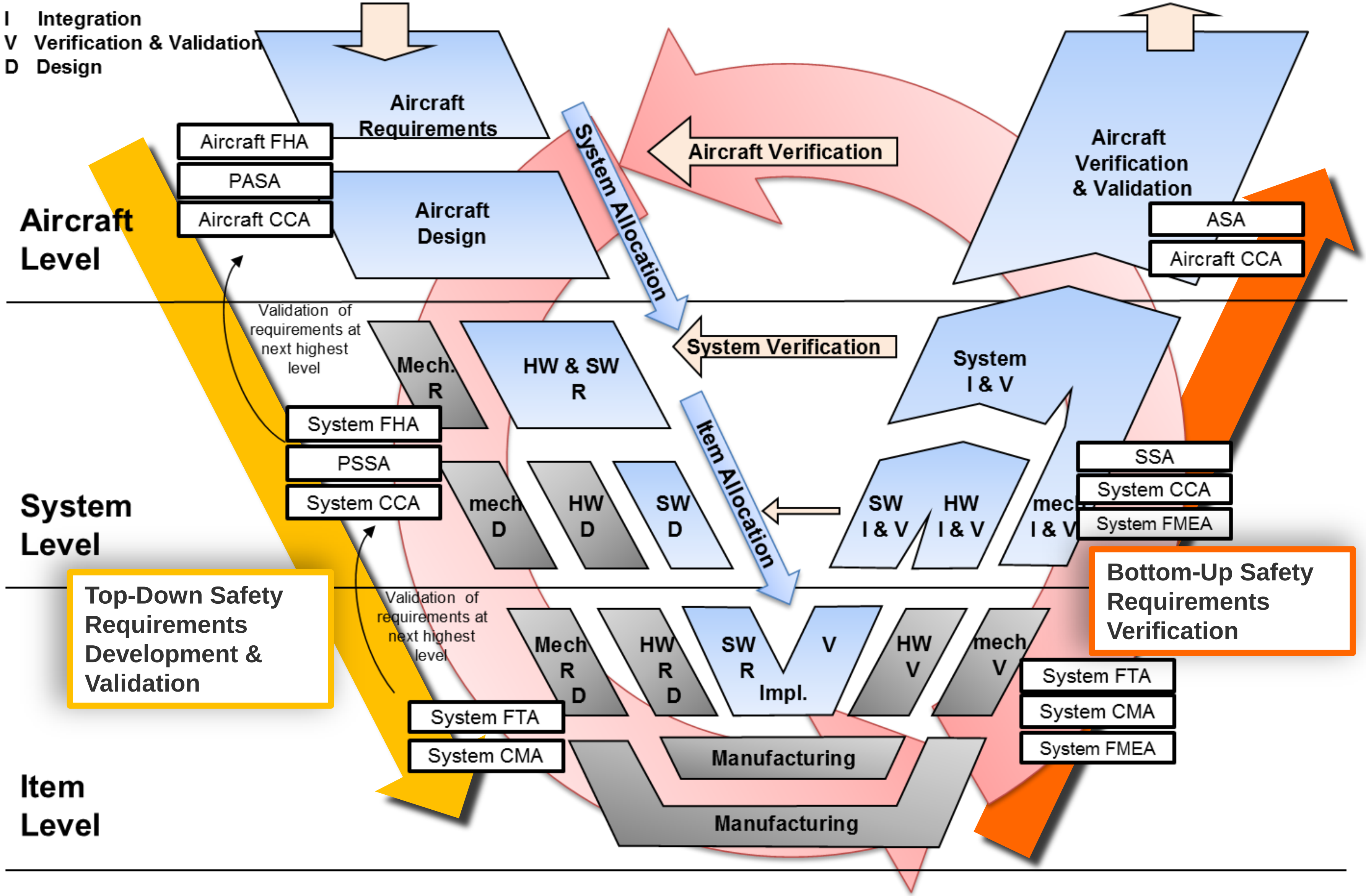
The Safety Assessment Process must be a combination of top-down and bottom-up activities for a holistic approach to system safety!

What happens if essential components fail?



Making Visions Fly

Interaction of Safety Assessment & Development Processes



CS-23.1309 Equipment, systems and installations

(b) The design of each item of equipment, each system, and each installation must be examined separately and in relationship to other aeroplane systems and installations to determine if the aeroplane is dependent upon its function for continued safe flight and landing …

Each item of equipment, each system, and each installation identified by this examination as one upon which the aeroplane is dependent for proper functioning to ensure continued safe flight and landing, or whose failure would significantly reduce the capability of the aeroplane or the ability of the crew to cope with adverse operating conditions, must be designed to comply with the following additional requirements:

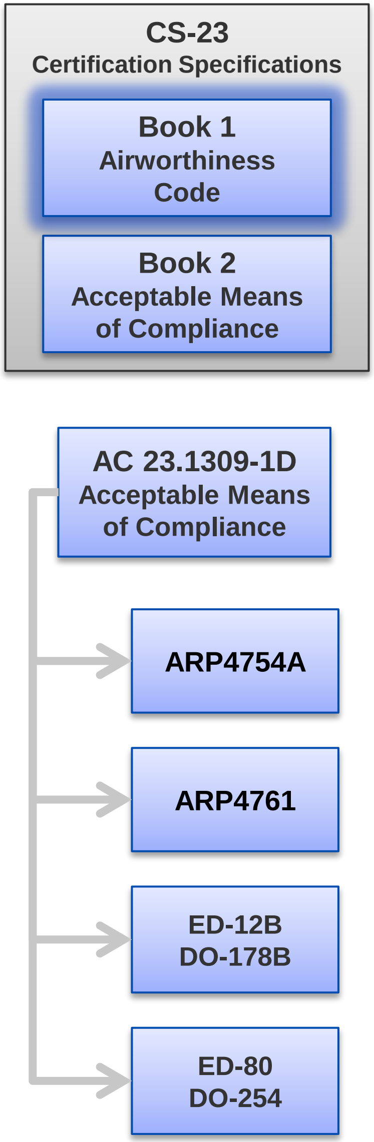
(1) It must perform its intended function under any foreseeable operating condition.

(2) When systems and associated components are considered separately and in relation to other systems –

(i) The occurrence of any failure condition that would prevent the continued safe flight and landing of the aeroplane must be **extremely improbable**

(ii) The occurrence of any other failure condition that would significantly reduce the capability of the aeroplane or the ability of the crew to cope with adverse operating conditions must be **improbable**.

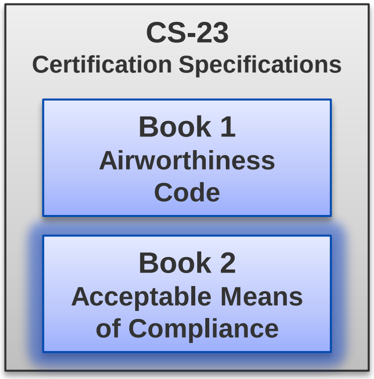
How probable is improbable / extremely improbable?



Making Visions Fly
Acceptable Means of Compliance

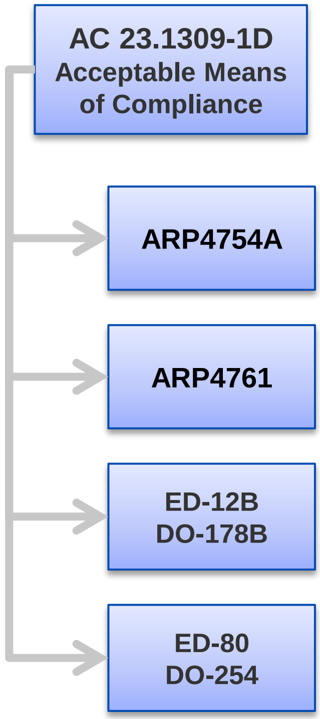
EASA CS-23 Book 2 - Acceptable Means of Compliance:

- What AMC's are available for Flight Control Systems?
- Book 2 of the CS-23 does not provide any acceptable means of showing compliance relevant for Digital Flight Control Systems.
- EASA Certification Review Item GA/G/001 refers to AC (Advisory Circular) 23.1309-1D from the FAA for showing compliance with §23.1309



Development Guidelines:

- **SAE ARP4754 Revision A** (issued Dec 2010):
  "Guidelines for Development of Civil Aircraft and Systems"
- **SAE ARP4761** (issued December 1996)
  "Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment"
- **RTCA DO-178B** (issued December 1992)
  "Software Considerations in Airborne Systems and Equipment Certification"
- **RTCA DO-254** (issued April 2000)
  "Design Assurance Guidance for Airborne Electronic Hardware"



These standards outline methods – but not the only methods – of showing compliance with the Advisory Circular AC 23.1309 and therefore to the § 23.1309.

Making Visions Fly

Acceptable Means of Compliance

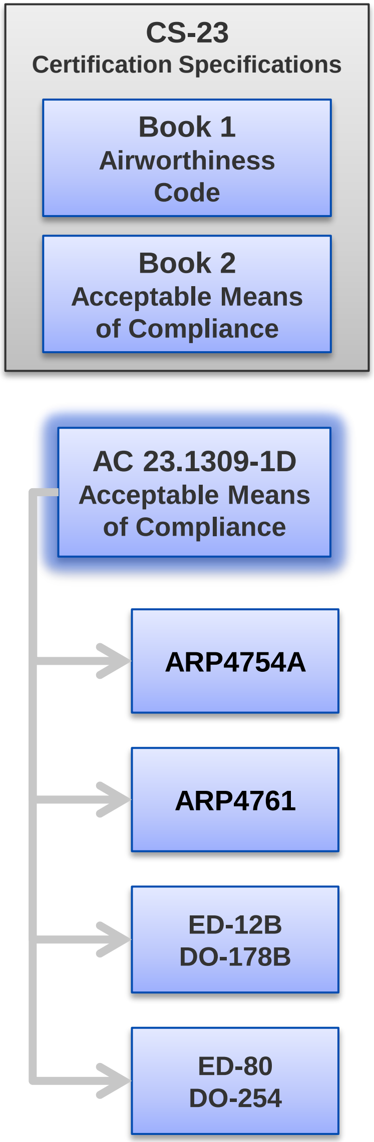
Classification of Failure Conditions	No Safety Effect	<----Minor----->	<----Major---->	<--Hazardous--->	< Catastrophic>
Allowable Qualitative Probability	**No Probability Requirement**	**Probable**	**Remote**	**Extremely Remote**	**Extremely Improbable**
Effect on Airplane	No effect on operational capabilities or safety	Slight reduction in functional capabilities or safety margins	Significant reduction in functional capabilities or safety margins	Large reduction in functional capabilities or safety margins	Normally with hull loss
Effect on Occupants	Inconvenience for passengers	Physical discomfort for passengers	Physical distress to passengers, possibly including injuries	Serious or fatal injury to an occupant	Multiple fatalities
Effect on Flight Crew	No effect on flight crew	Slight increase in workload or use of emergency procedures	Physical discomfort or a significant increase in workload	Physical distress or excessive workload impairs ability to perform tasks	Fatal Injury or incapacitation
Classes of Airplanes:	**Allowable Quantitative Probabilities and Software (SW) and Complex Hardware (HW) DALs (Note 2)**				
Class I (Typically SRE under 6,000 lbs.)	No Probability or SW & HW DALs Requirement	$<10^{-3}$ Note 1 & 4 P=D, S=D	$<10^{-4}$ Notes 1 & 4 P=C, S=D P=D, S=D(Note 5)	$<10^{-5}$ Notes 4 P=C, S=D P=D, S=D(Note 5)	$<10^{-6}$ Note 3 P=C, S=C
Class II (Typically MRE, STE, or MTE under 6000 lbs.)	No Probability or SW & HW DALs Requirement	$<10^{-3}$ Note 1 & 4 P=D, S=D	$<10^{-5}$ Notes 1 & 4 P=C, S=D P=D, S=D(Note 5)	$<10^{-6}$ Notes 4 P=C, S=C P=D, S=D(Note 5)	$<10^{-7}$ Note 3 P=C, S=C
Class III (Typically SRE, STE, MRE, & MTE equal or over 6000 lbs.)	No Probability or SW & HW DALs Requirement	$<10^{-3}$ Note 1 & 4 P=D, S=D	$<10^{-5}$ Notes 1 & 4 P=C, S=D	$<10^{-7}$ Notes 4 P=C, S=C	$<10^{-8}$ Note 3 P=B, S=C
Class IV (Typically Commuter Category)	No Probability or SW & HW DALs Requirement	$<10^{-3}$ Note 1 & 4 P=D, S=D	$<10^{-5}$ Notes 1 & 4 P=C, S=D	$<10^{-7}$ Notes 4 P=B, S=C	$<10^{-9}$ [illegible] P=A, S=B

Note 1: Numerical values indicate an order of probability range and are provided here as a reference. The applicant is usually not required to perform a quantitative analysis for minor and major failure conditions. See figure 3.
Note 2: The alphabets denote the typical SW and HW DALs for most primary system (P) and secondary system (S). For example, HW or SW DALs Level A on primary system is noted by P=A. See paragraphs 13 & 21 for more guidance.
Note 3: At airplane function level, no single failure will result in a catastrophic failure condition.
Note 4. Secondary system (S) may not be required to meet probability goals. If installed, S should meet stated criteria.
Note 5. A reduction of DALs applies only for navigation, communication, and surveillance systems if an altitude encoding altimeter transponder is installed and it provides the appropriate mitigations. See paragraphs 13 & 21 for more information.

"FIGURE 2. RELATIONSHIP AMONG AIRPLANE CLASSES, PROBABILITIES, SEVERITY OF FAILURE CONDITIONS, AND SOFTWARE AND COMPLEX HARDWARE DALs"

Classification of Failure Conditions and Probability:

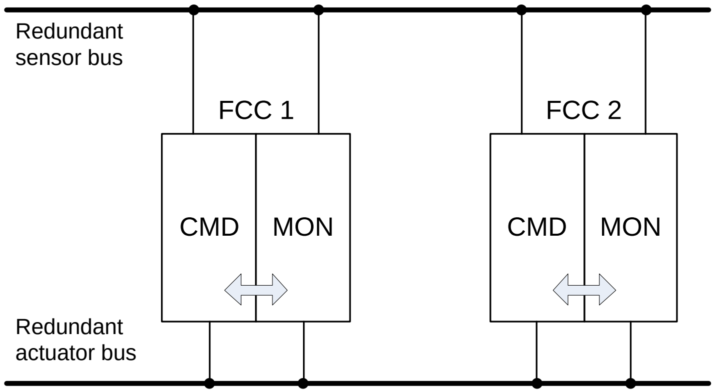
- Minor $< 10^{-3}$
- Major $< 10^{-5}$
- Hazardous $< 10^{-7}$
- Catastrophic $< 10^{-9}$



Example

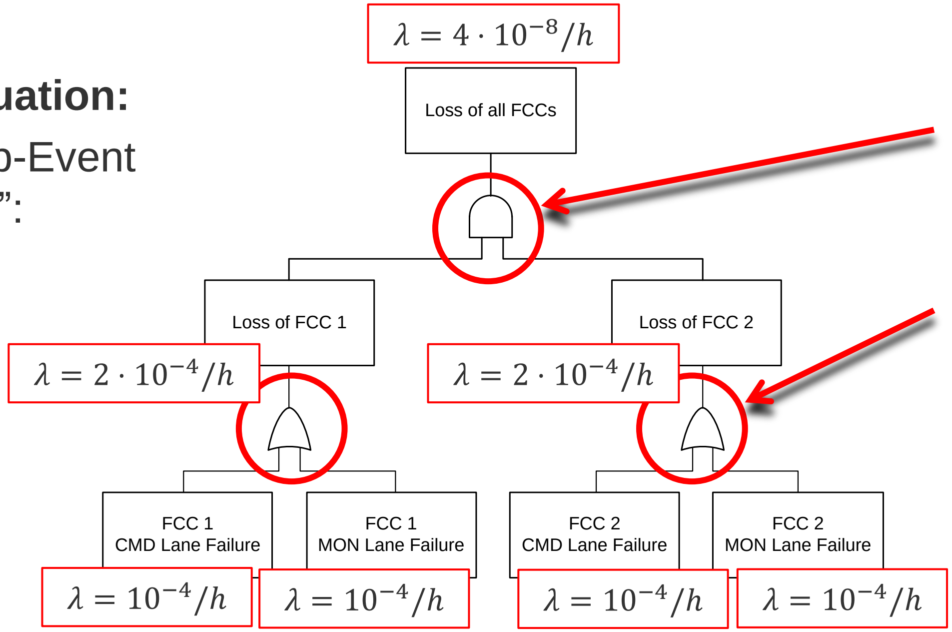
Fail-Op Dual-Duplex FCS

- Two FCCs, each with one command and one monitor lane.
- If command or monitor lane fail, entire FCC is passivated.
- FCS failure if both FCCs fail



Qualitative Evaluation:

Fault Tree for Top-Event "Loss of all FCCs":

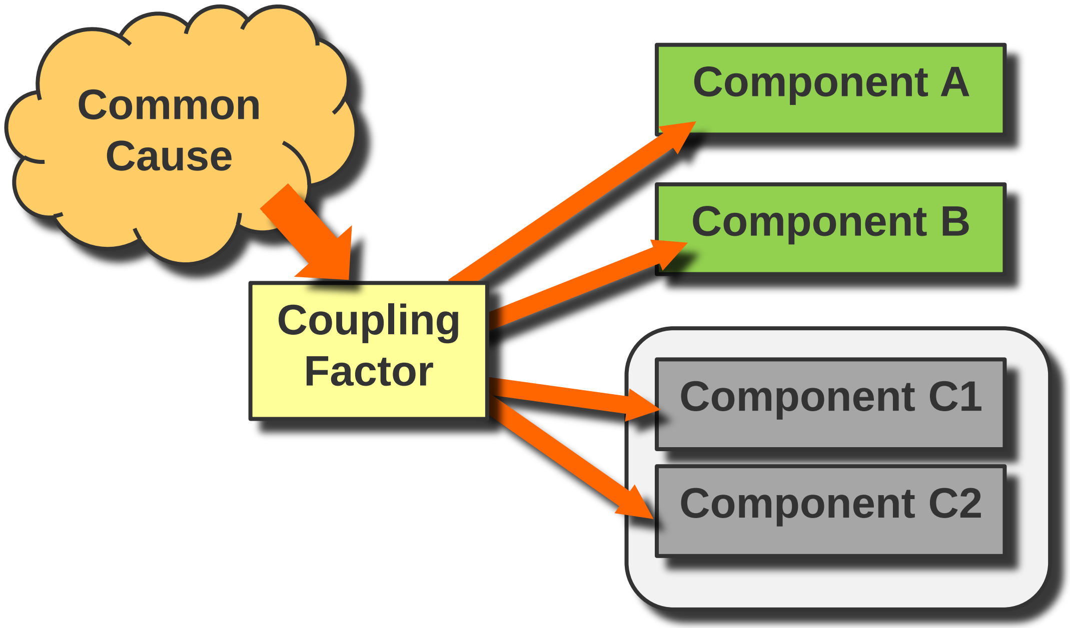


Loss of FCS if FCC1 AND FCC 2 are lost

Loss of FCC1/2 if Command OR Monitor Lane fails

⇨ Formulation of derived requirements considering safety aspects.

- A common cause analysis (CCA) examines the proposed aircraft or system architecture(s) to ensure that independence between functions, systems or items required to satisfy safety or regulatory requirements exists.
- The CCA identifies individual failure modes or external events that can lead to catastrophic or hazardous failure conditions. It consists of the following analyses.



Patricular Risk Analysis (PRA):

Particular Risks are events or incidents affecting the system from the outside:

- EMI / HIRF,
- Hail, Ice, Snow
- Bird strikes
- Fire, Smoke,
- Enginge rotor burst, tyre burst, …

Common Mode Analysis (CMA):

A CMA is a simulateous failure of multiple components otherwise considered redundant, e.g. due to:

- Software error (OS, libraries, compiler)
- Hardware (processor, layout, …)
- Power supply

Zonal Safety Analysis (ZSA):

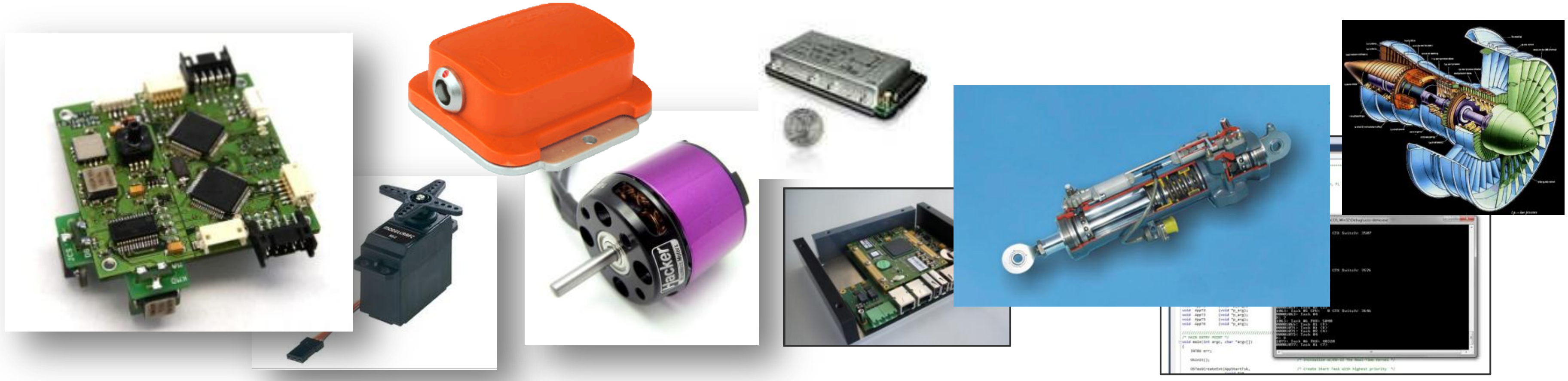
Ensure that installation meet safety requirements regarding interference between systems, potential cascade failures, environmental factors, maintenence errors etc.

Making Visions Fly

Consideration of System and Component Specific Behavior

- Consideration of the characteristics of involved systems and subsystems
  - ⇨ Sensors
  - ⇨ Actuators
  - ⇨ computers
  - ⇨ communication channels
- Analysis of available sensors and measurement data
- Data fusion principles
- Component specific tradeoffs concerning:
  - ⇨ Availiability
  - ⇨ Price
  - ⇨ Accuracy and precision
  - ⇨ Integration effort
  - ⇨ Reliability
  - ⇨ Error behaviour
- Redundancy Concepts

Making Visions Fly
Consideration of System and Component Specific Behavior

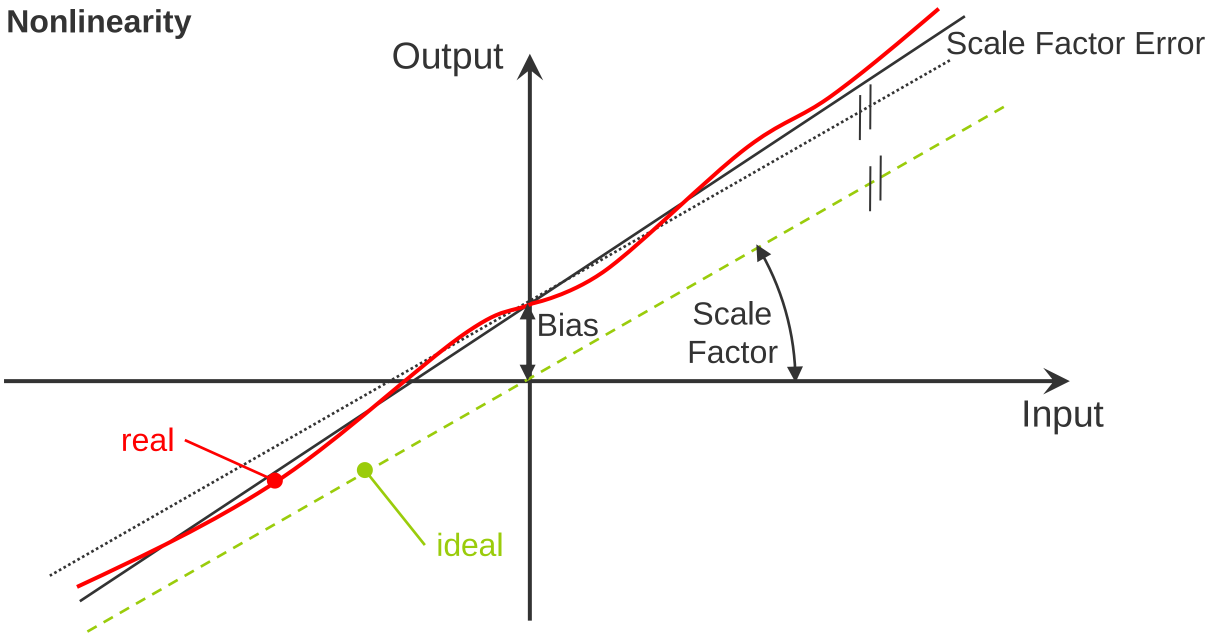


The most important FCS Components are:	
FCC (Flight Control Computer)	redundant, dissimilar architectures
Data busses	aerospace specific busses like ARINC 429
Sensors	like IMU, AHRS, GPS, ADS, …
RTOS or **Scheduler**	for deterministic real time execution of periodically called controller functions and I/O handling
Application Program	including control algorithm, moding logic, health monitoring, …
Actuators	EMA, EHA

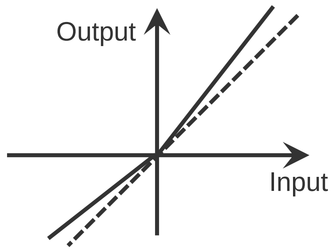
⇨ Multi- domain system, which fulfils its functionality by interaction of all components on overall system level (closed – loop including aircraft)

Sensor measurements are normally faulty. The output signal differs from the input acceleration to be measured.

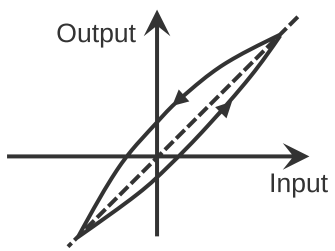
Bias, Scale Factor Error, Nonlinearity



Asymmetry

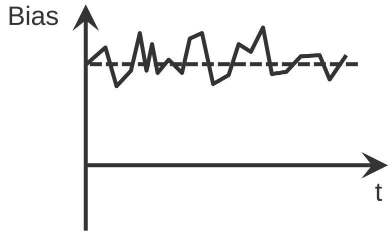


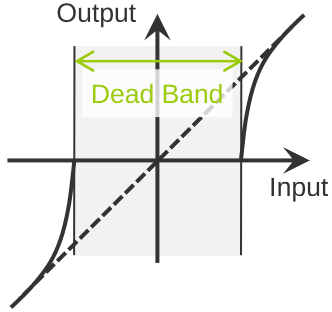
Hysteresis

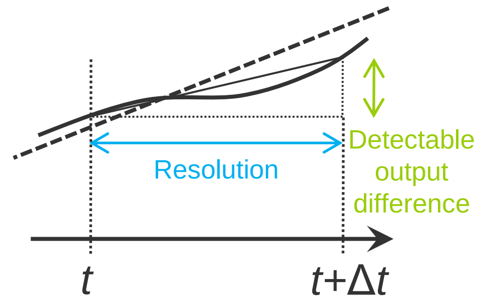


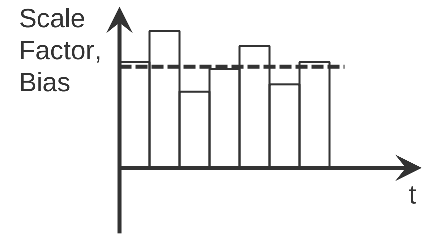
- *Bias*: Non-zero output value even though there is no input
- *Scale Factor Error*: Deviation of the output / input ratio from the ideal scale factor
- *Nonlinearity*: Non-linear scale factor
- *Asymmetry*: Different scale factors for positive and negative inputs
- *Hysteresis*: Different outputs for increasing and decreasing inputs

Making Visions Fly
Sensor Errors (2)

Bias Instability


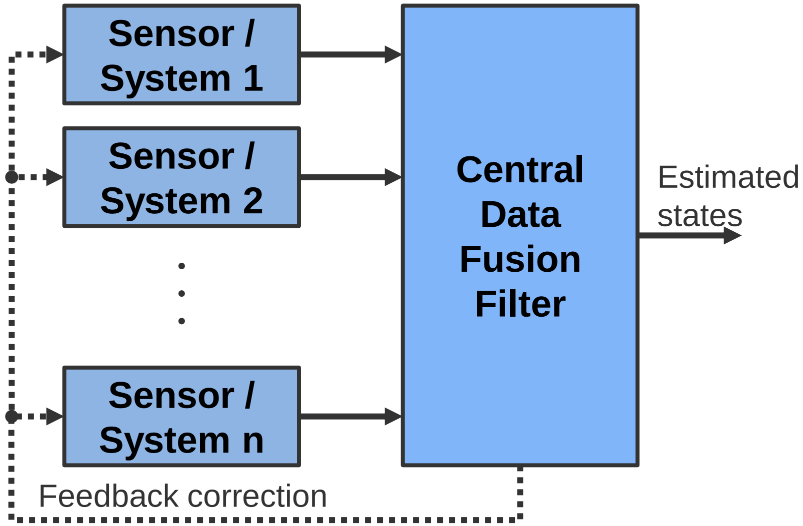
Dead Band


Resolution


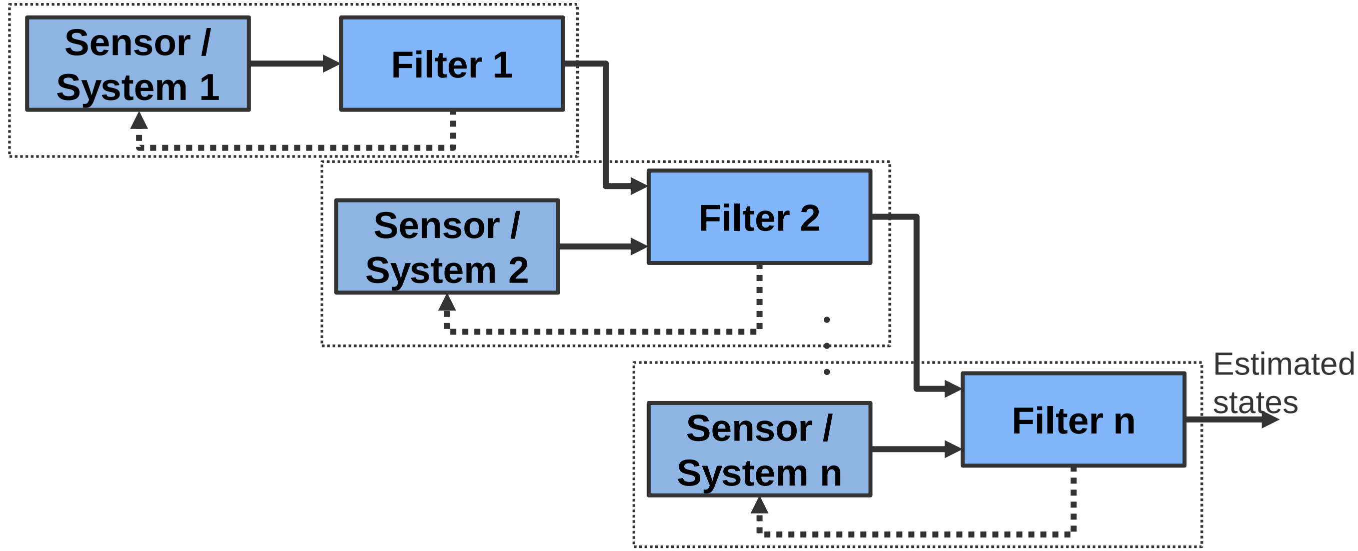
Turn-On Bias


• *Bias Instability*:	Random medium to long-term bias variation
• *Dead Band, Threshold*:	Small area around null where inputs are not detected e.g. due to stiction
• *Resolution/Quantization*:	Minimum measurable input/floating point representation
• *Turn-On Bias*:	Variation of scale factor and bias from day-to-day
• *Misalignment*:	Non-orthogonality of sensor axes
• *Noise:*	Random short-term variation
• *Temperature Effect:*	Sensor errors caused by temperature variation

Centralized Data Fusion Architecture:



Cascaded Data Fusion Architecture:



Hardware Redundancy

Similar sensors	Similar navigation systems	Dissimilar systems/sensors
Sensor-level redundancy	*System-level redundancy*	
e.g. multiple inertial sensors	e.g. dual, triple or quadruple INS	e.g. INS, GPS, radio navigation, air data, magnetic heading

Analytical Redundancy

Kinematic Models

- Translational
  - Position, velocity ODE
- Rotational
  - Orientation ODE

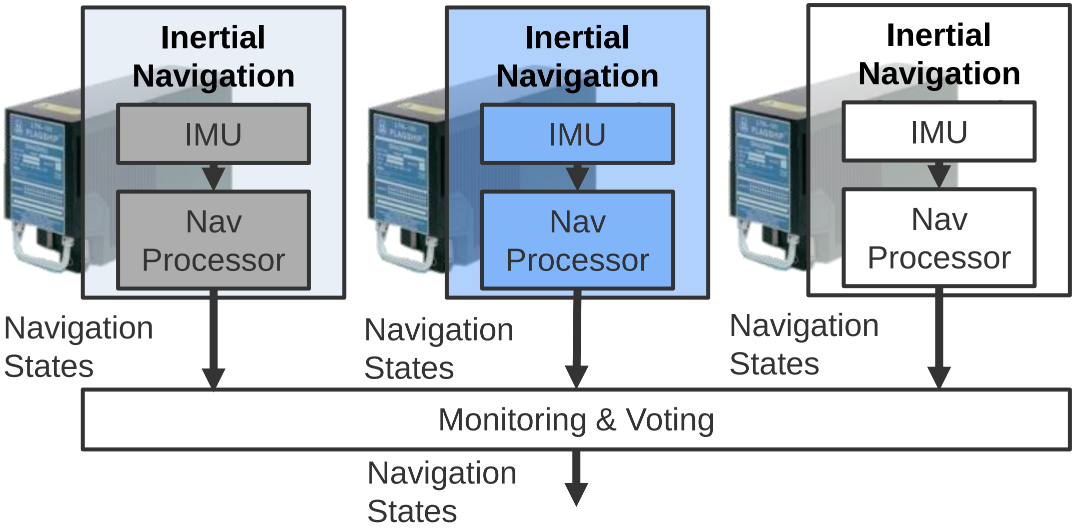
Dynamic Models

- Translational
- Rotational

e.g. plausibility tests

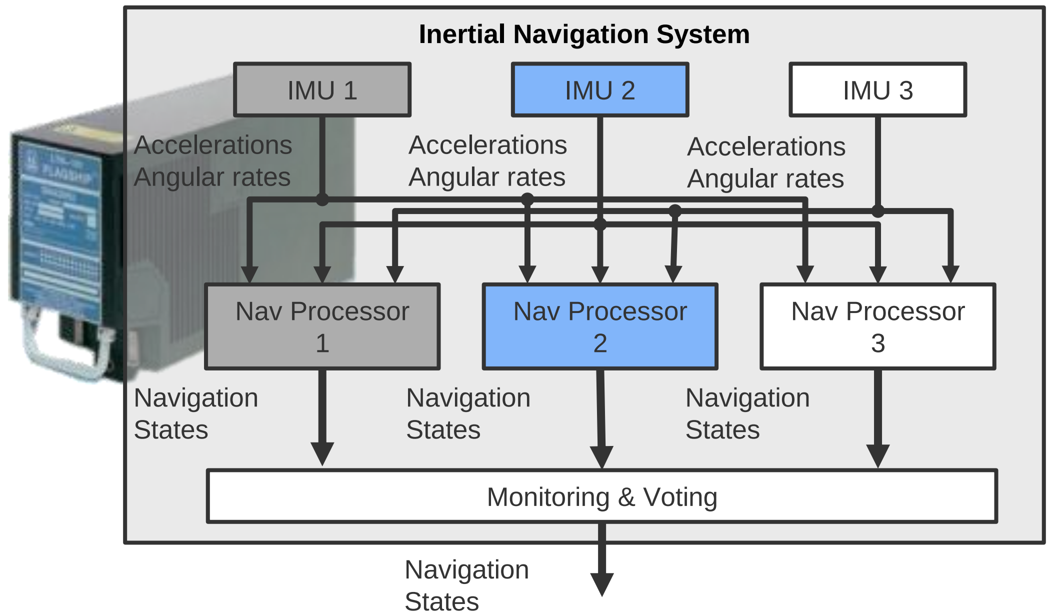
e.g. change of position with time vs. velocity

Software Redundancy



System Level Redundancy

Sensor Level Redundancy



COTS ADAHRS with internal GPS

Advantages

- Low integration effort

Disadavantages

- No integrity information on GPS(VPL, HPL)
- No GBAS functionality available

COTS ADAHRS and external GPS (SBAS / GBAS)

Advantages

- Medium integration effort

Disadavantages

- Inconsistent navigation solution
  (GPS vs. IMU)
  Sensor Data Fusion required

COTS ADAHRS aided by external GPS (SBAS / GBAS)

Advantages

- Medium integration effort
- Consistent navigation solution

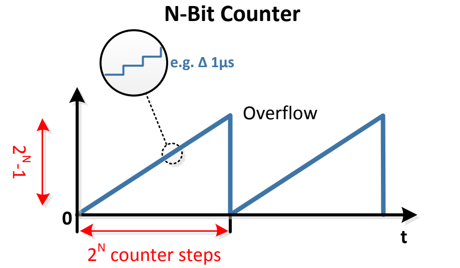
Disadavantages

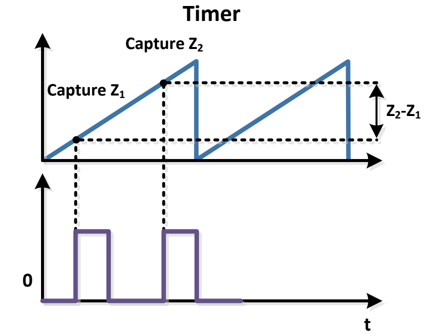
- No integrity information of resulting navigation solution from GPS aided AHRS

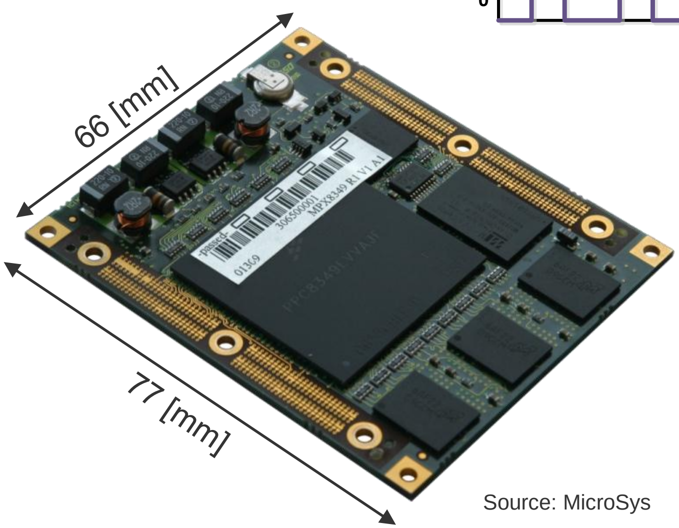
Additional things to be considered

- High precision altitude sensor integration and data fusion for consistency and integrity of vertical navigation channel during approach
- Integrity monitoring of VPL, HPL and other integrity information
- Provision of integrity Information to GCS
- Degree of redundancy in navigation solution

- Implementation aspects on real-time systems
  - ⇨ Synchronization of independent systems
  - ⇨ Timings
  - ⇨ Latencies
  - ⇨ Jitter
  - ⇨ Determinism
  - ⇨ Bus-load analyses
  - ⇨ Maximum system loads
- Real-time OS and driver layer
- Framework development
- Nominal and failure handling modes

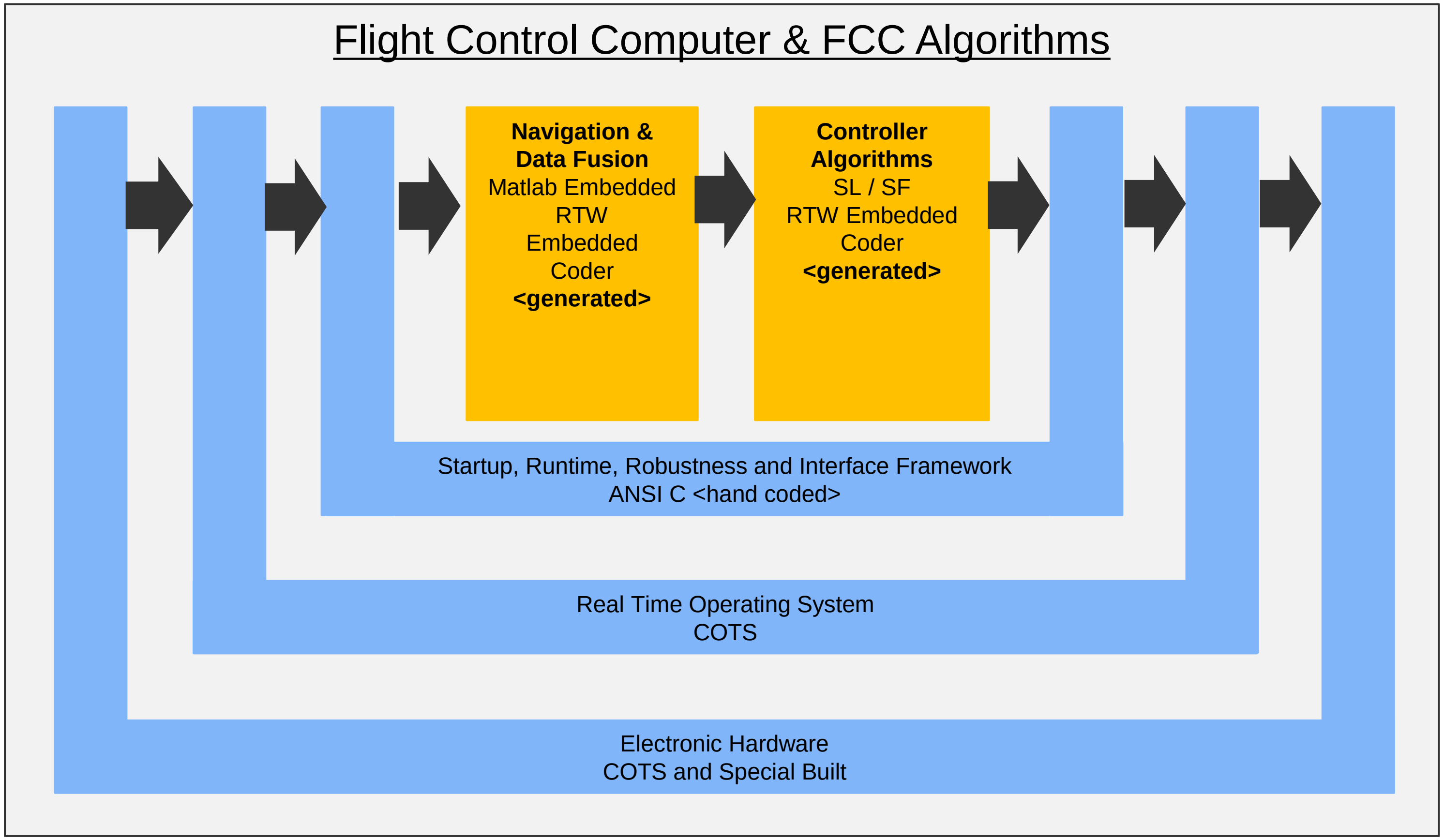






Source: MicroSys

Making Visions Fly
Real-time Systems



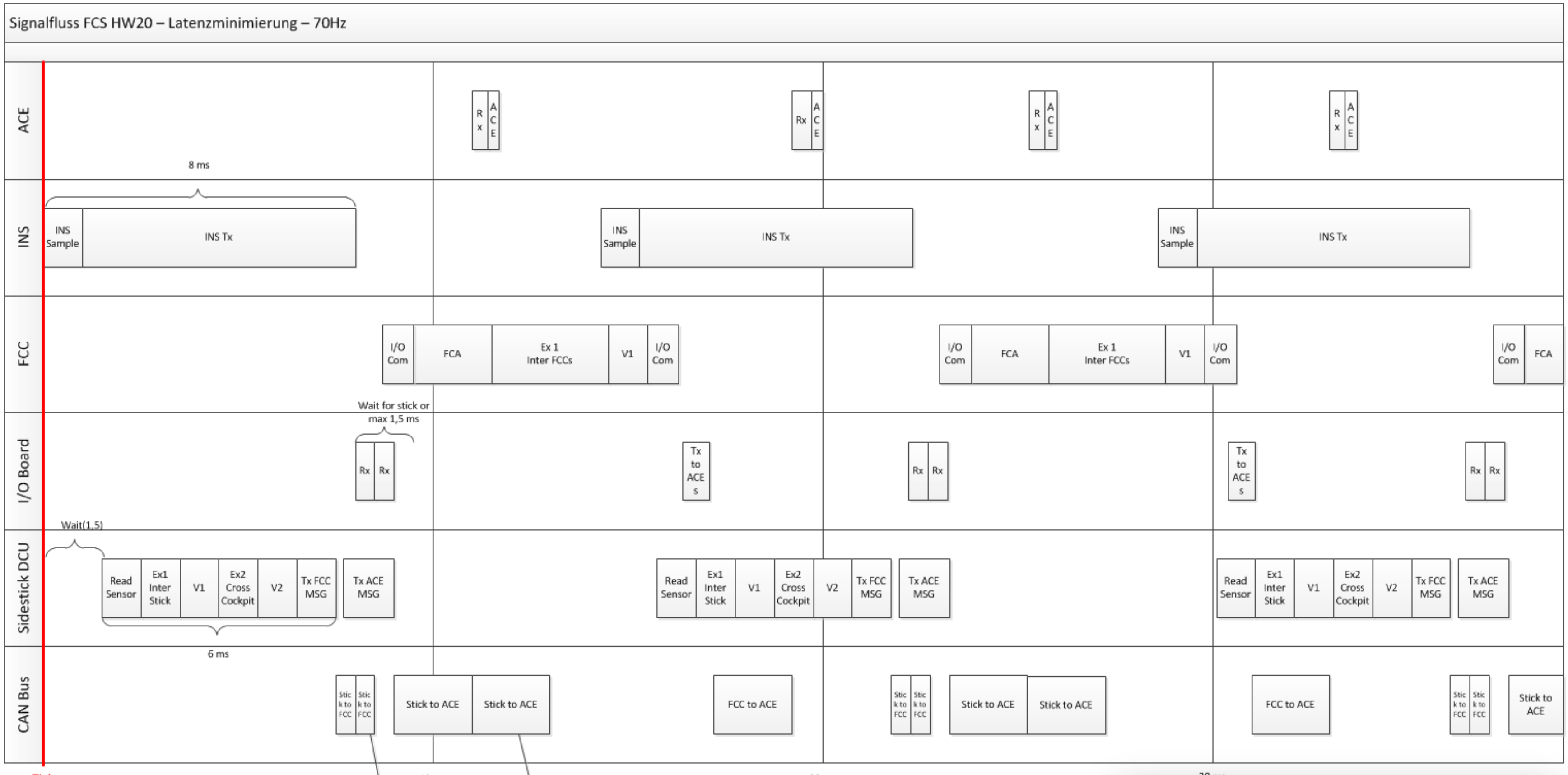
Certification regulations

Defacto standards

Development process

Development guidelines

Making Visions Fly
Timings and Latencies

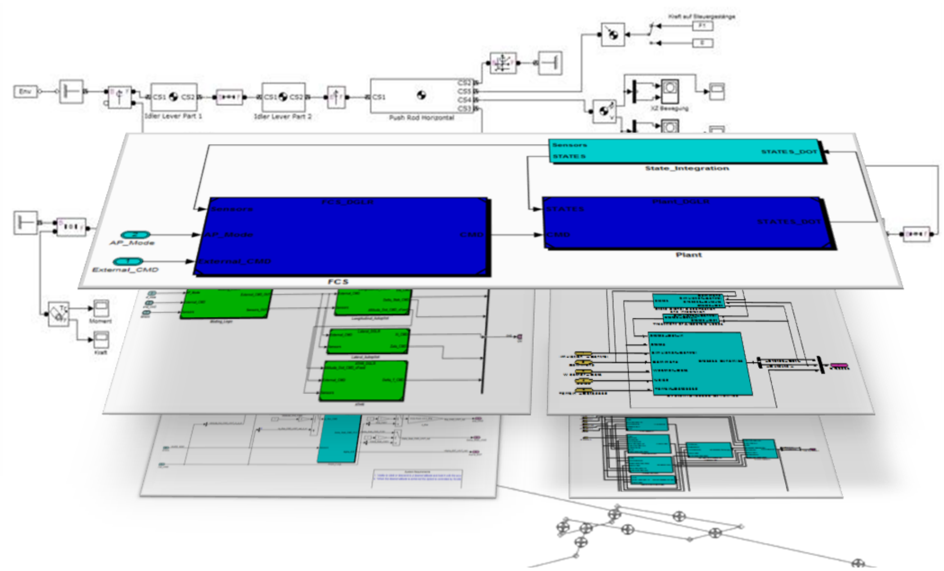


- The more complex the simulation model gets, the more detailed the reality will be represented.

  ⇨ **Objective: simulation of the overall system!**

- Attempt to model as many uncertainties, characteristics and external influences as possible

- Anticipation of problems and obstacles in the simulation



Foreseeable obstacles to be adressed already in simulations

Plant uncertainties

- Parametric uncertainties (aerodynamic coefficients, weight and balance, …)
- Simplifications and unmodelled dynamics (dynamic order of subsystems, aeroelastics, …)
- Unknown dynamics (nonlinear structure of aerodynamics, interferences, …)

Atmospheric disturbances

- Turbulence, Gusts
- Wind

Hardware characteristics

- Sensor measurements (noise, bias, outliers, delays …)
- Digitalization effects (quantization, data types, delays,...)
- Flight control computer (processor load, interrupt and I/O-handling,…)
- Equivalence between simulated control laws and compiled and linked code on target

Foreseeable obstacles to be adressed already in simulations

Correctness of implementation and coverage over operational envelope

- Implementation flaws(Initialization, Anti-Integrator wind up and reset, interfaces, …)
- Verification Coverage (consideration of all operational conditions)

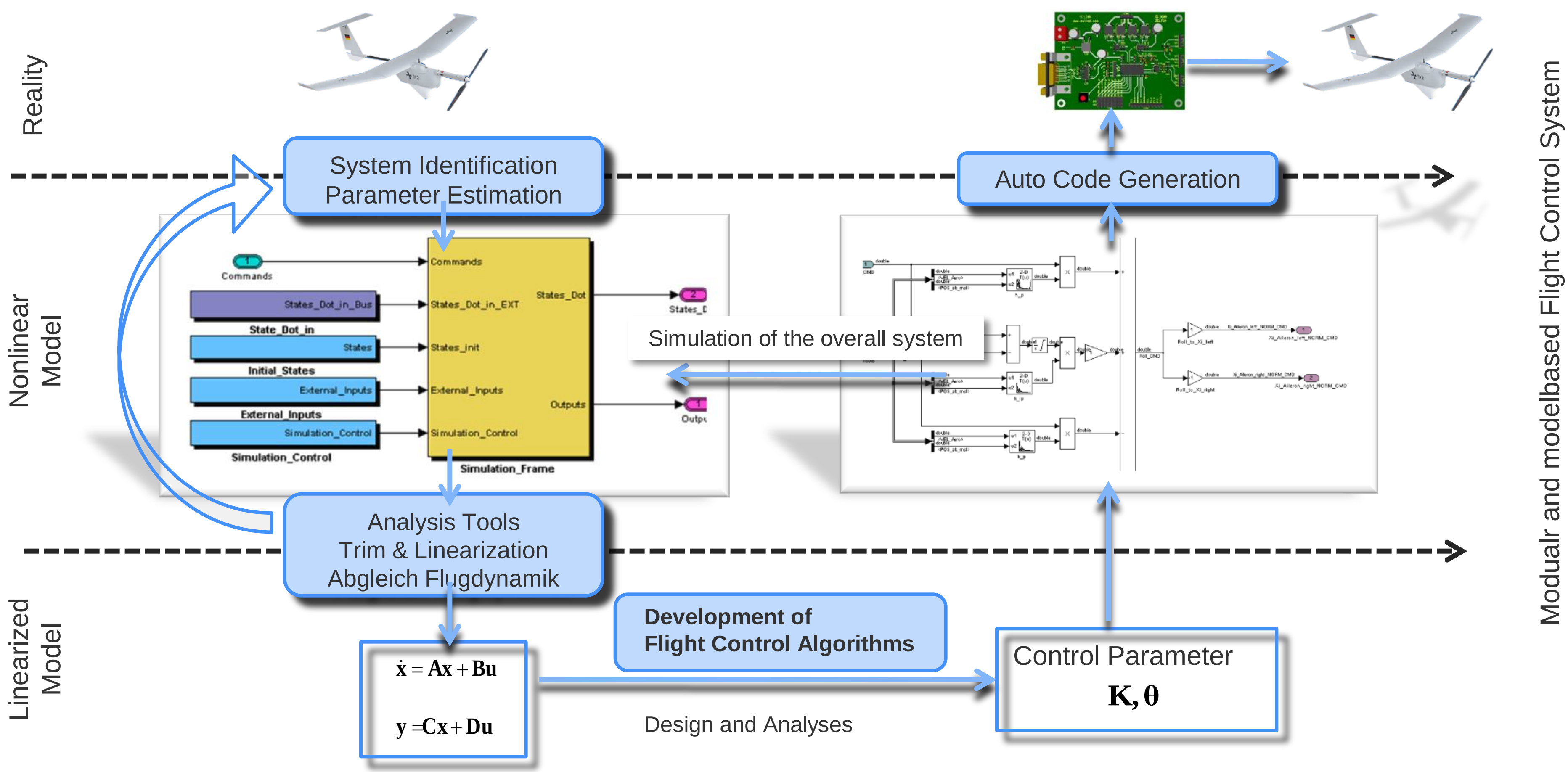
=> Closed loop simulations can address these obstacles…

- Model-in-the-Loop
- Software-in-the-Loop
- Hardware-in-the-Loop
- Processor-in-the-Loop

=> … Many of them even without a validated model

Adaption of the simulation model to reality with the help of parameter estimation and system identification as an iterative process!

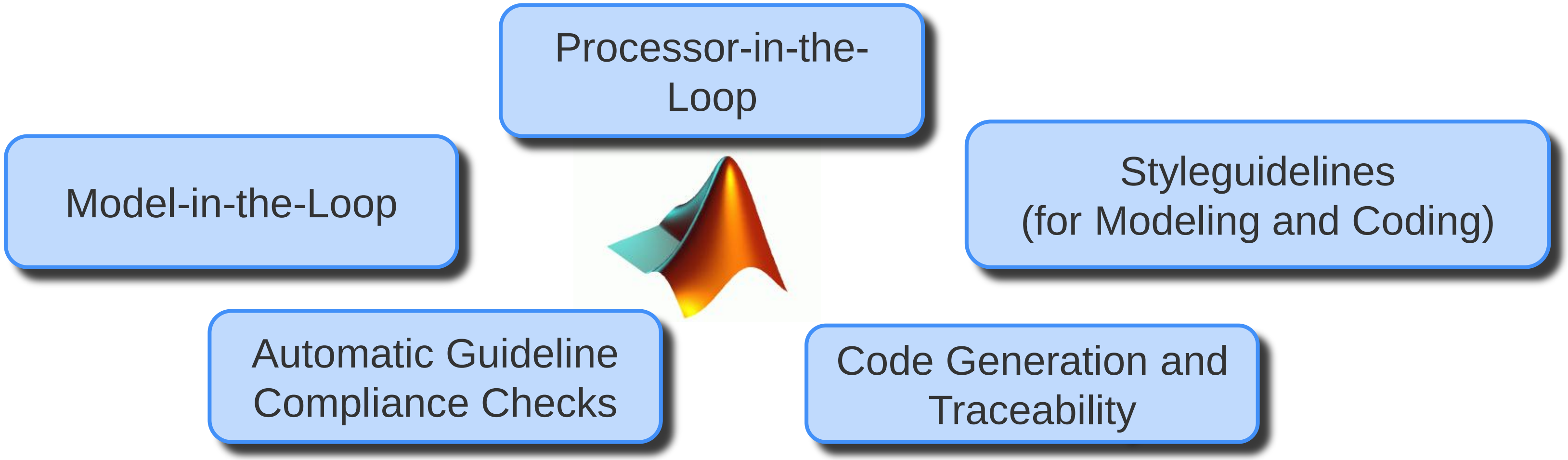
Making Visions Fly
Modelbased Development Process



- Performance can be increased by the use of high-level development systems at simultaneous control of functional complexity
- The development process can be almost entirely computer based
- Deterministic and reproducible development

Aspects of implementation:

- Proceedings during implementation
- Styleguidelines
- Model-in-the-Loop simulation
- Code generation and requirement tracing
- Processor-in-the-Loop simulation
- Hardware-in-the-Loop simulation
- Iron-Bird testing



Design Standards

Code Standards

Guideline Name

Guideline ID →

Scope →

Possible Automation →

Description →

Example →

Penalties →

← Compliant with

← Priority

← Benefits

Simulink Guidelines V [illegible].1

Lehrstuhl für Flugsystemdynamik – Institute of Flight System Dynamics

ID[1]	NAME[2]	
SL_16.	Block Resizing	
SCOPE[3]	PRIORITY[4]	COMPLIANT WITH[5]
☒ON BOARD ☒SIMULATION	☒MANDATORY ☐ STRONGLY RECOMMENDED ☐RECOMMENDED	☐ARP 4754 ☐DO 178 – B ☐ MISRA – C

AUTOMATION[6]

none

PREREQUISITES[7]

none

DESCRIPTION[8]

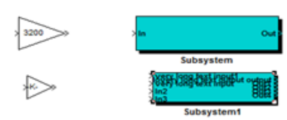
- All blocks in a model must be sized such that their icon is completely visible and recognizable.
- In particular, any text (e.g. tunable parameters, filenames, equations) in the icons must be readable.

Note:
This guideline requires resizing blocks with variable icons or blocks with a variable number of in- and outputs

EXAMPLES[9]

Correct

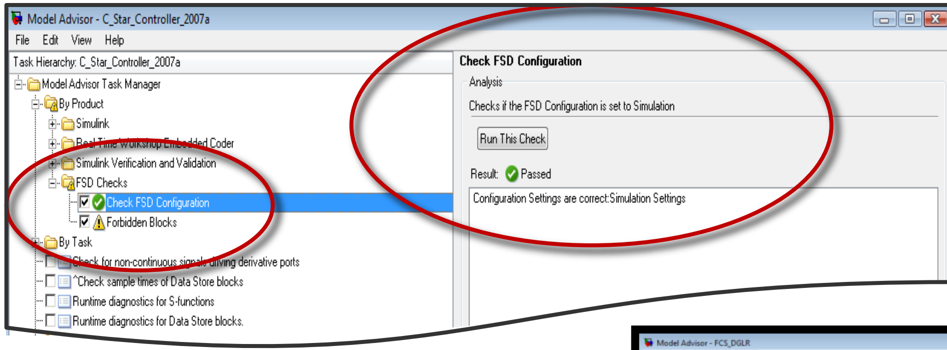
Incorrect

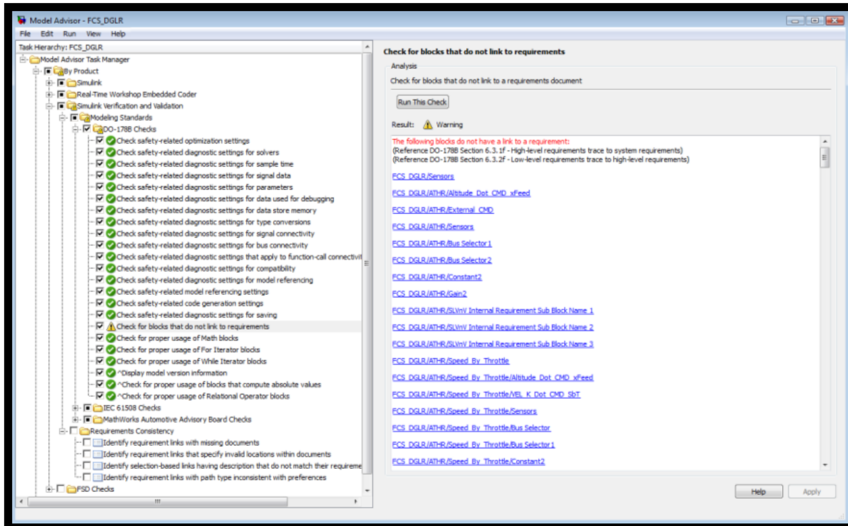


PENALTIES	BENEFIT
• unreadable models. • problems in understanding the model	• readable models • understandable presentations
LAST UPDATE(NAME/DATE)[10]	Surinowitsch / 06/10/2009

Stanislav Surinowitsch Page 27

Verification of guideline compliance with model advisor and custom FSD rules

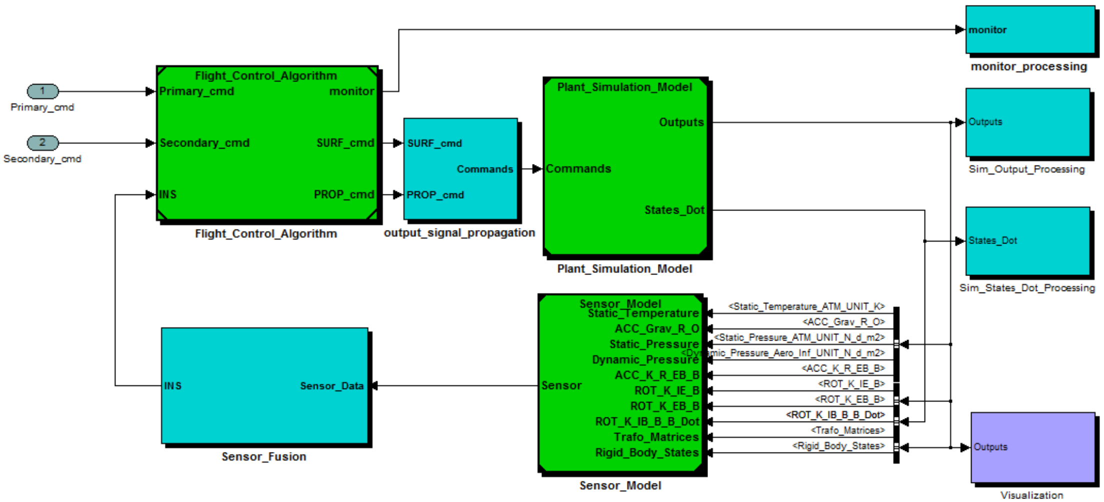




Objectives:

- DO 178B compliance, FSD styleguidelines compliance
- Automatic generation of compliance reports

Model-in-the-loop test harness layout



Test objectives

- **All related requirements are covered**
- **All foreseeable obstacles are adressed**
- 100% model coverage achieved
- Test cases and results are well presented
- Test cases are repeatable and automated

Definition of a verification plan

	Simulink Models Verification Standard	Date	2010-10-19
		Rev	V-0001
	Verification Plan and Results	Page	38 / 50

3.5 Verification of Operational Requirements

3.5.1 Testing Environment

Test Harness:				3–323
Folder				3–324
Test Model Name				3–325
Link				3–326
Type of Test	Time-based simulation ☐		Single-point execution ☐	3–327
Data Generation	Specified Data ☐	Gridding ☐	Stochastic ☐	3–328
Check Mechanism	Off-Line Comparison ☐		On-Line Comparison ☐	3–329

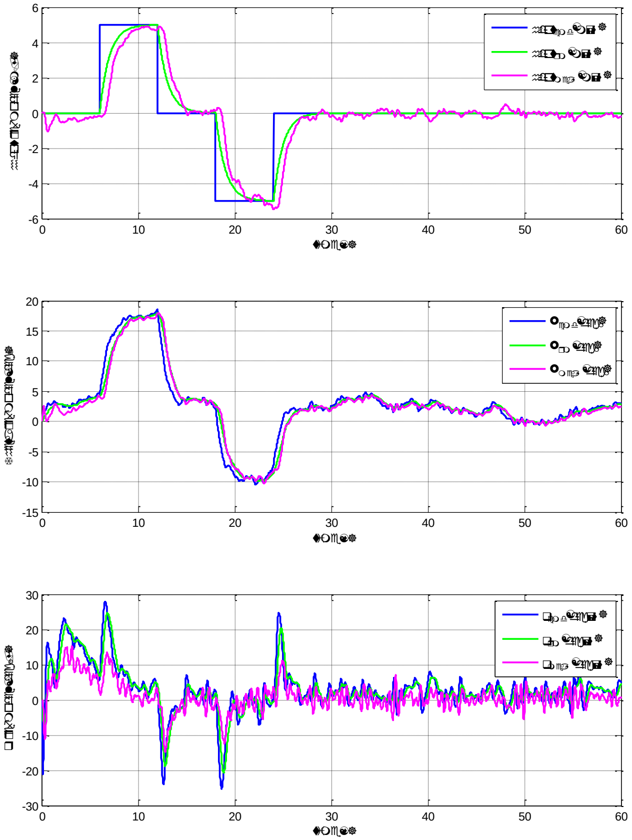
Output Signal Dependencies			
Outputs		Names of Required Inputs	3–330
No	Name		

Test Hardware				
CPU	Type			3–331
	Speed			
RAM	Type			
	Speed			
	Memory			
HDD	Type			
	Speed			
	Memory			
OS				
Matlab				

3.5.1.1 Structural Layout of the Test Harness

Link to HTML established by Export to Web Functionalility
For algorithmic systems (e.g. Embedded Matlab): Nassi-Shneiderman diagrams
For state transition logics: State Graphs
For dynamic process models: Block diagrams

- **Complete system functionality can be built up and verified, e.g. up to mission flight**

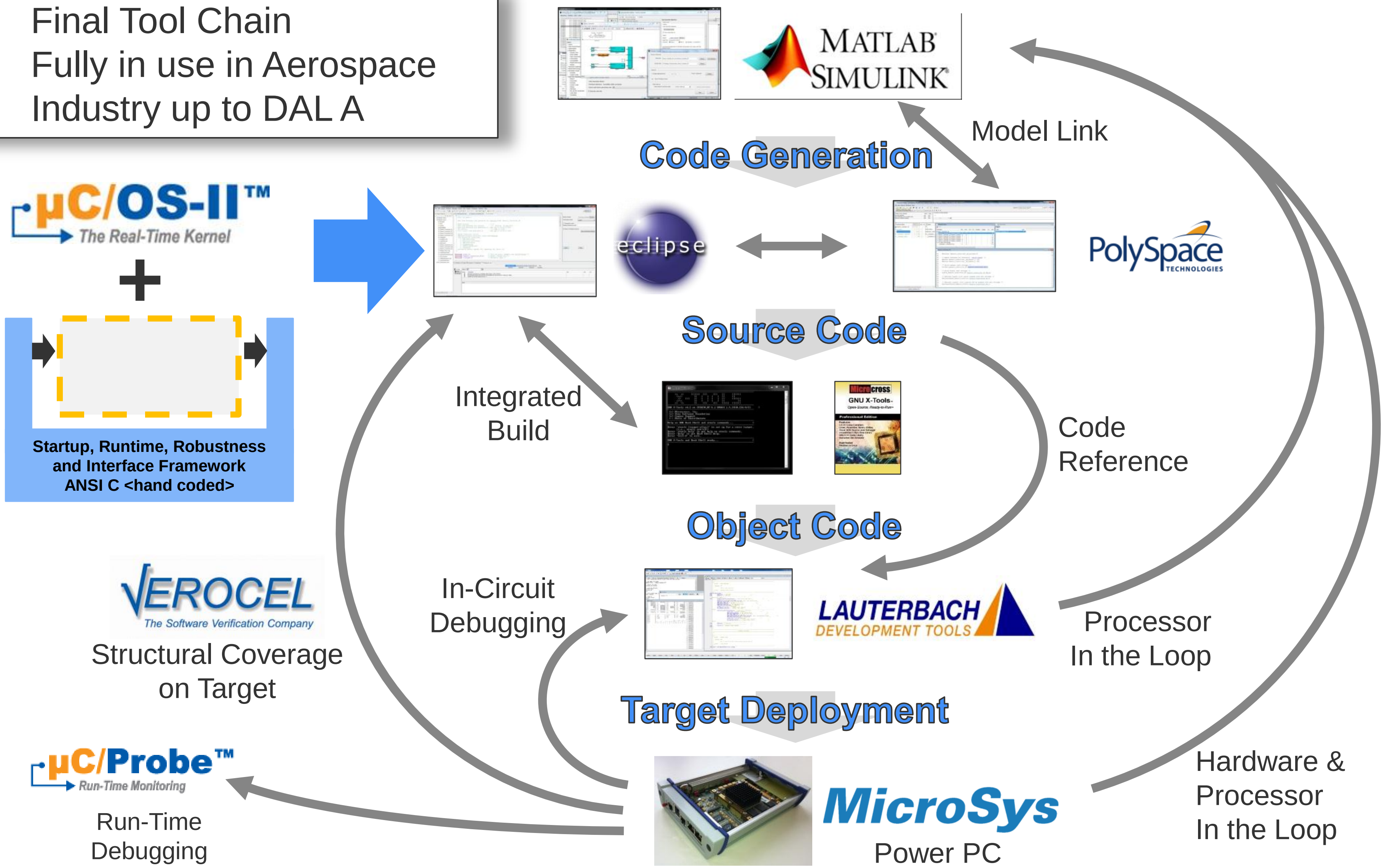


- **Closed-loop simulation is a key advantage for modelbased verification**

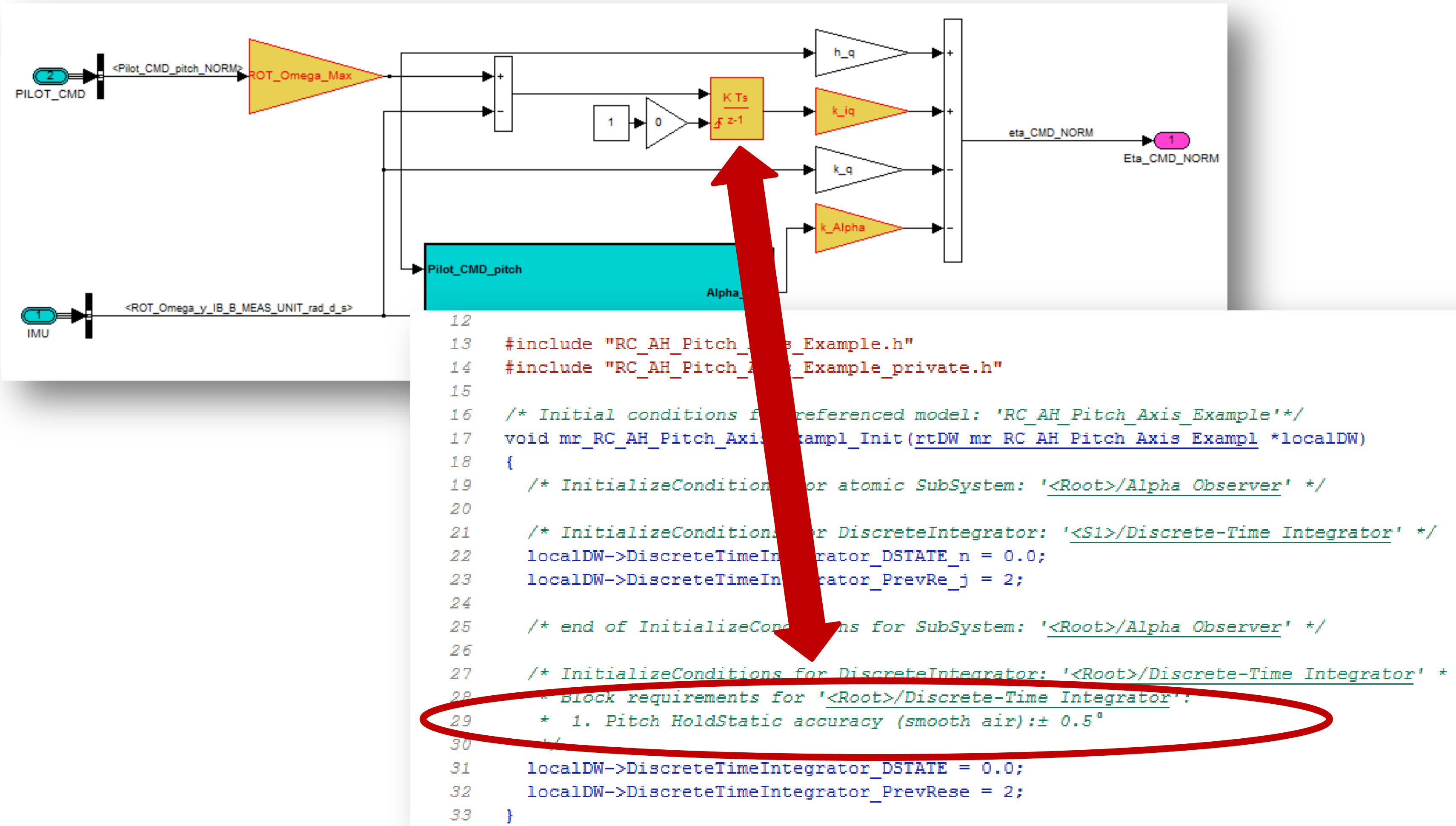
- **Code generation and target deployment is effectively eased**

Making Visions Fly
Tool Chain Structure and Workflow for Power PC

- Final Tool Chain
- Fully in use in Aerospace Industry up to DAL A

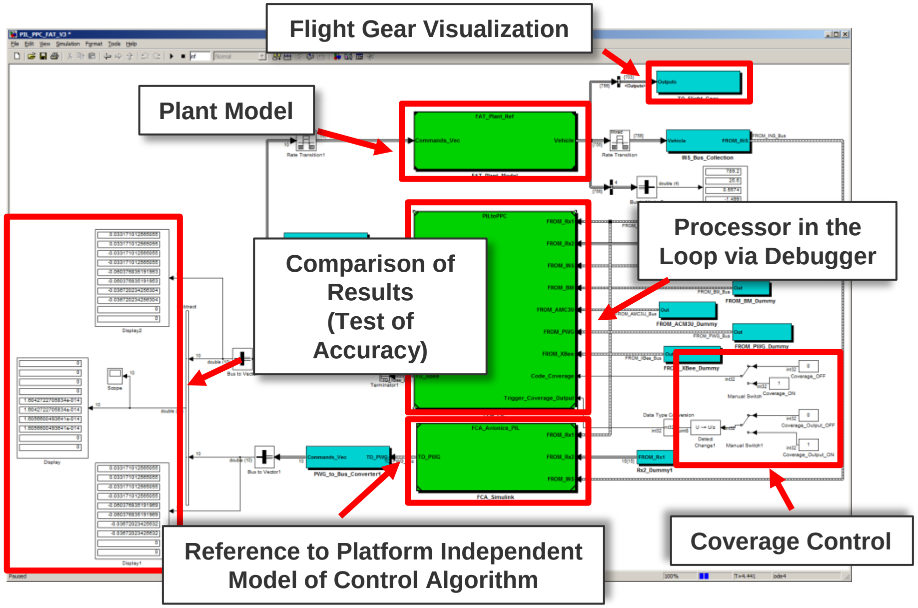


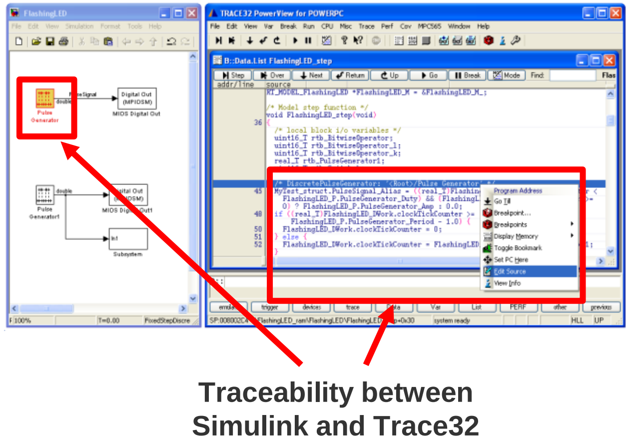
Code generation and requirement tracing



General Description

- New approach for PIL:
  - ✓ No instrumentation of target software
  - ✓ Final software product including all frameworks, drivers and operating system
  - ✓ Communication via JTAG
  - ✓ Compatible to auto generated code and handwritten code
- Focus on numerical accuracy on target processor (e.g. differences in libraries and floating point operations)
- Fully integrated in Simulink and TRACE32 Debugger
- Seamless debugging of generated code on real target (e.g. executable links between model and object code, definition of break points through Simulink block menu)
- Structural code coverage analysis on object code using either VerOCode or TRACE32

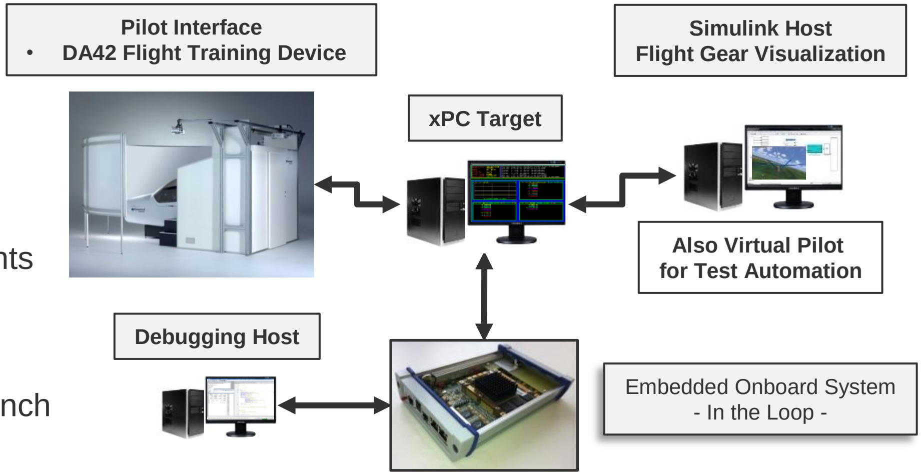




Additional information:
http://www.lauterbach.com/simulink_2012.pdf

General Description

- Test bench for integration testing of fly by wire system.
- Focus on performance, robustness and interface testing
- Reuse of controller development plant model and requirements based test cases.
- Integration of HIL testing and flight simulation through direct interface between DA42 flight training device and HIL test bench

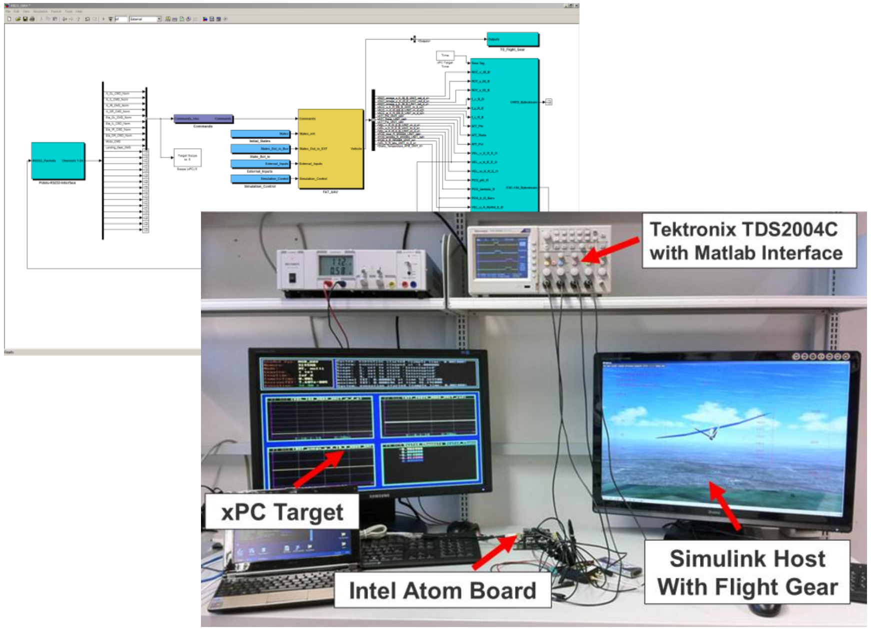


MathWorks xPC Target Simulation Desktop

- Real time operating system running on standard desktop computer
- Fully integrated within Matlab/Simulink
- Multiple I/Os through National Instrument PXI System (supported by xPC Target)

Additional Equipment

- Tektronix TDS2004C Oscilloscope
- Vector CANoe for ARINC825 simulation and testing
- Multiple Lauterbach Debuggers, 500MHz logic analyzer and stimuli generator
- B&R PLCs for simulation of bus devices



Diamond DA-42 Flight Training Device

General Description

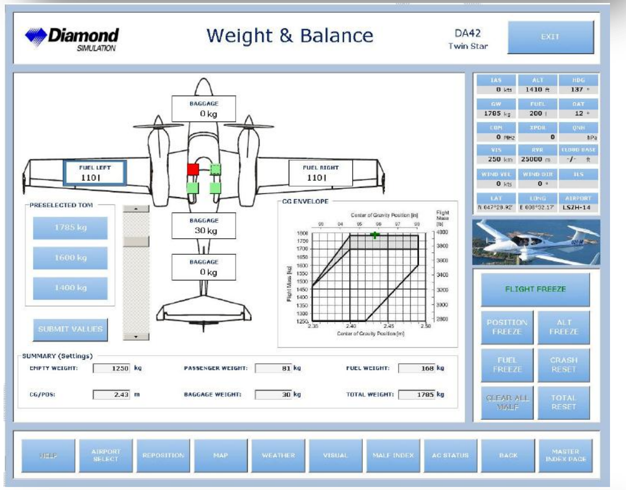
- Built with original aircraft components from Diamond Aircraft to achieve a most realistic cockpit environment
- Certifiable up to FTD Level 5+, Level 6 dynamics under development
- Accurate replication of aircraft flight dynamics and systems
- Original Garmin G1000 PFD and MFD hardware
- Electrically operated three-axes control loading system
- Multi-screen instructor operating station (IOS) aft of cabin
- Extensive capability to simulate malfunctions of multiple aircraft systems

Flight Dynamic Model (FDM)

- FDM includes accurate aerodynamics, engine, propeller and gear models
- Based on reference data from airframe manufacturer Diamond Aircraft and parameter estimation performed by Diamond Simulation

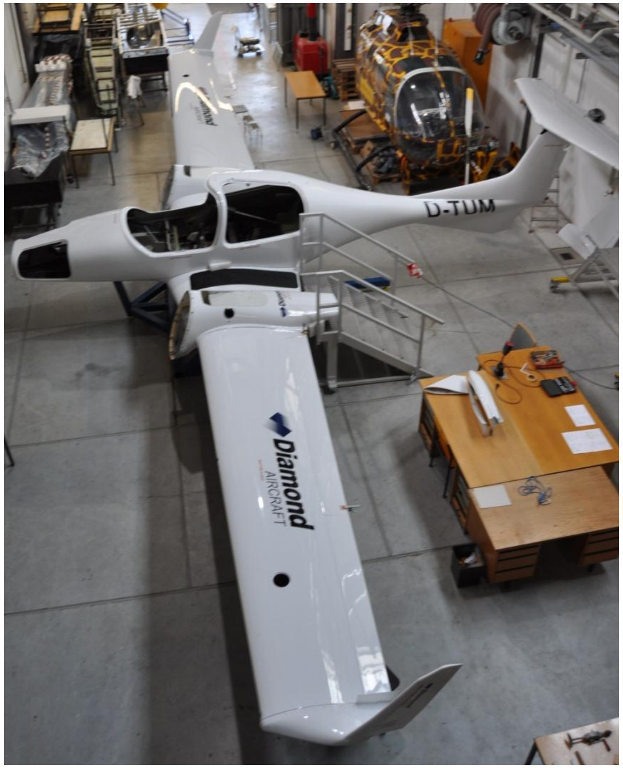
External Visual System (EVS)

- Three-channel external visual system (EVS) with 180-degree cylindrical screen
- Visual software: CAE Tropos 1000, based on full-flight EVS Tropos 6000
- Projection system and the visual databases meet certification requirements up to Level B Full Flight Simulators according to the regulations of the JAA and FAA



Making Visions Fly
Iron-Bird-Testing

- Testing and analysis of flight control systems
- Test of hardware components embedded in the real system environment
  - ⇨ Actuators
  - ⇨ Clutches
  - ⇨ Intervention to flight controls
- Test of handling qualities
- Test of safety mechanisms
- Test of faults and automatic fault recovery
- Hardware-in-the-Loop-Testing / Interface to D-Sim42 NG Simulator



Thank you very much for your attention!