System Identification within Flight Test and Flight Physics

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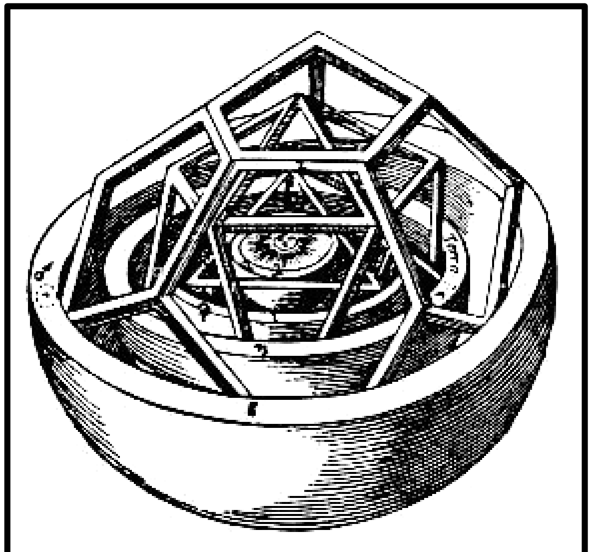
A project proposal

Alejandro Valverde

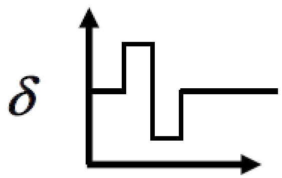
Aircraft System Identification

System Identification **is the process of building mathematical models for physical systems based on imperfect observations or measurements**



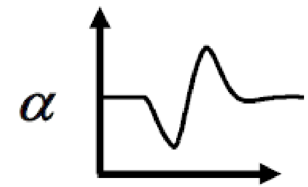
When applied to aircraft, it is called
Aircraft System Identification

Problems in Aircraft Dynamics



Input, *u*

System, *S*



Output, z

Simulation: Given *u* and *S*, find z

Control: Given *z* and *S*, find *u*

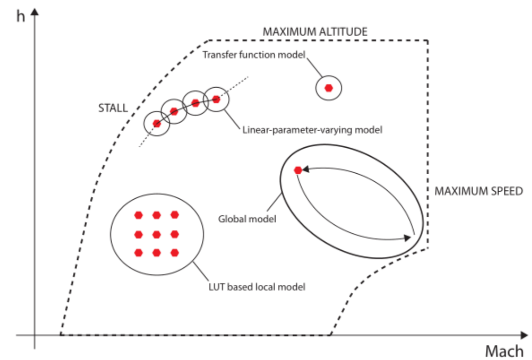
Identification: Given *z* and *u*, find *S*

Applications of Aircraft System ID techniques

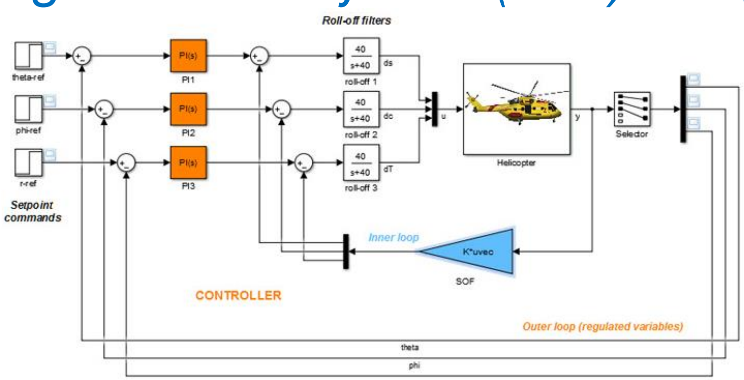
Aircraft System Identification offers a wide range of different applications, including:

Flight Simulator development


Flight envelope expansion



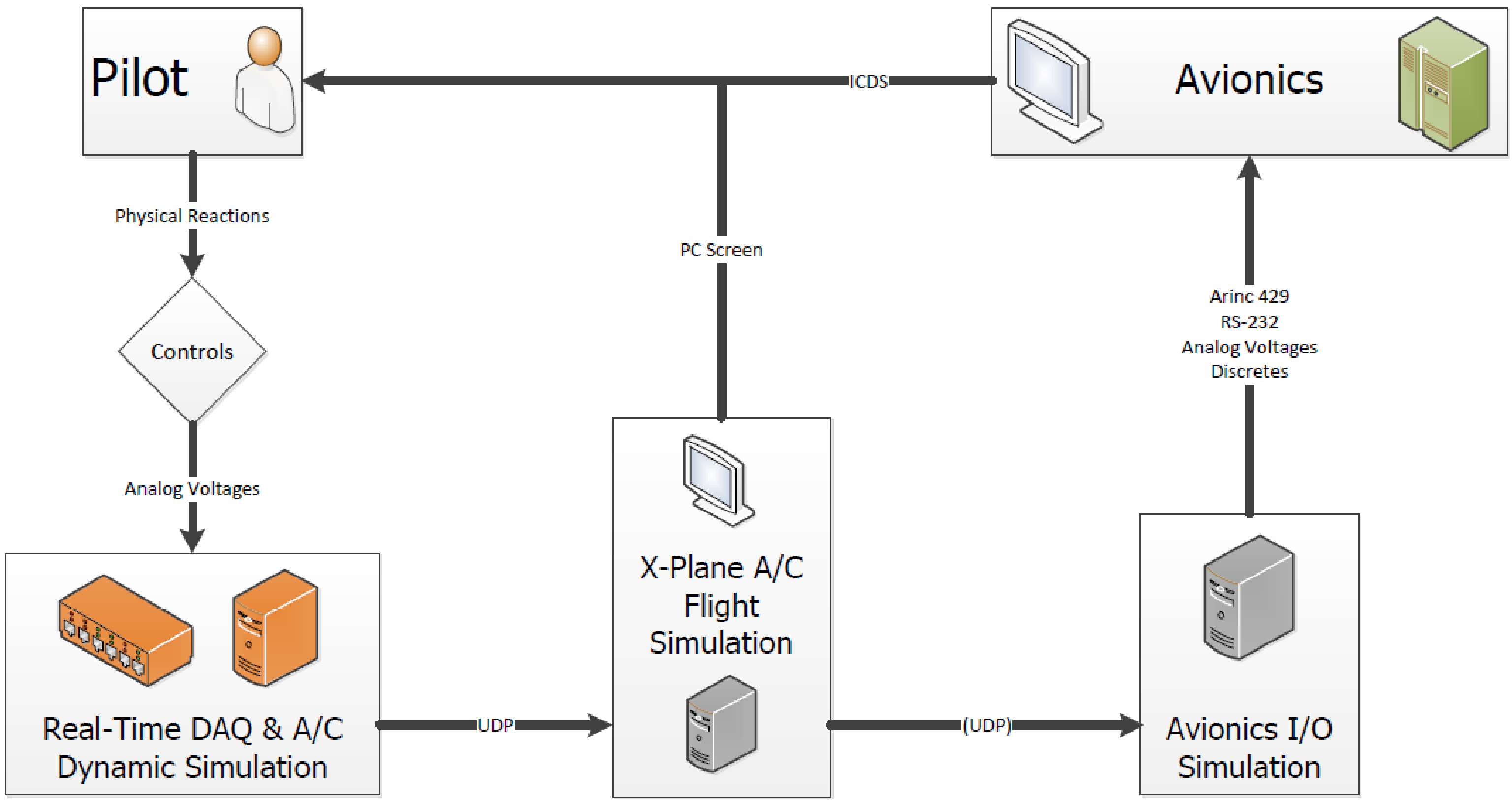
Flight Control System (FCS) design



Handling Qualities assessment and enhancement

And many others…

Aircraft Simulation - Ongoing Kopter project



Extracted from Nicolas Callejo's MSc Thesis overview in collaboration with Kopter Avionics Dep.

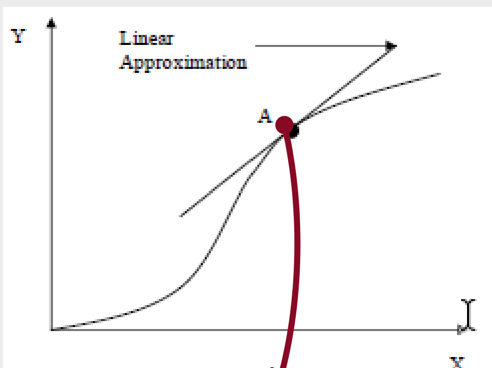
Aircraft Simulation – Current Kopter approach

Dynamic Simulation

Non-linear model

Trimmed condition of FlightLab, e.g.:

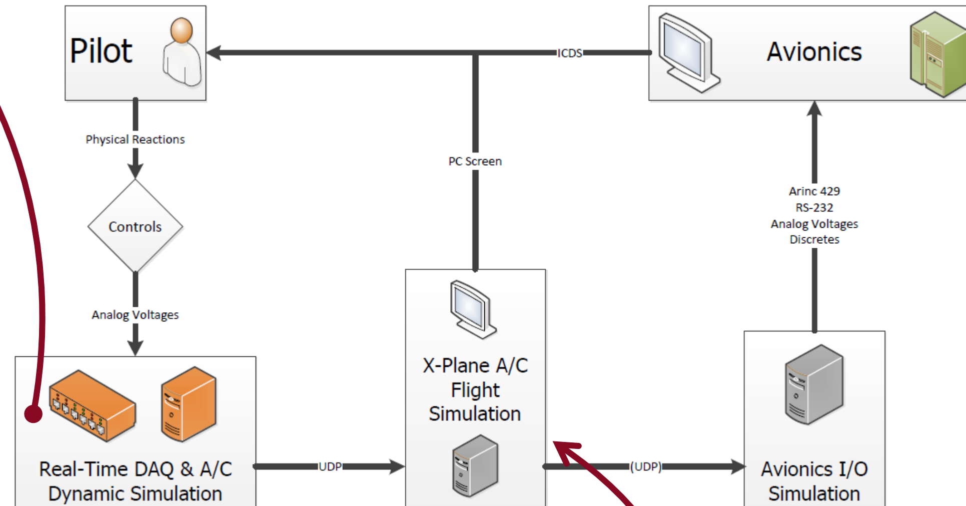
➡ fwd level flight @ 100kts



Linear model

linearization of full H/C dynamics in LTI model:

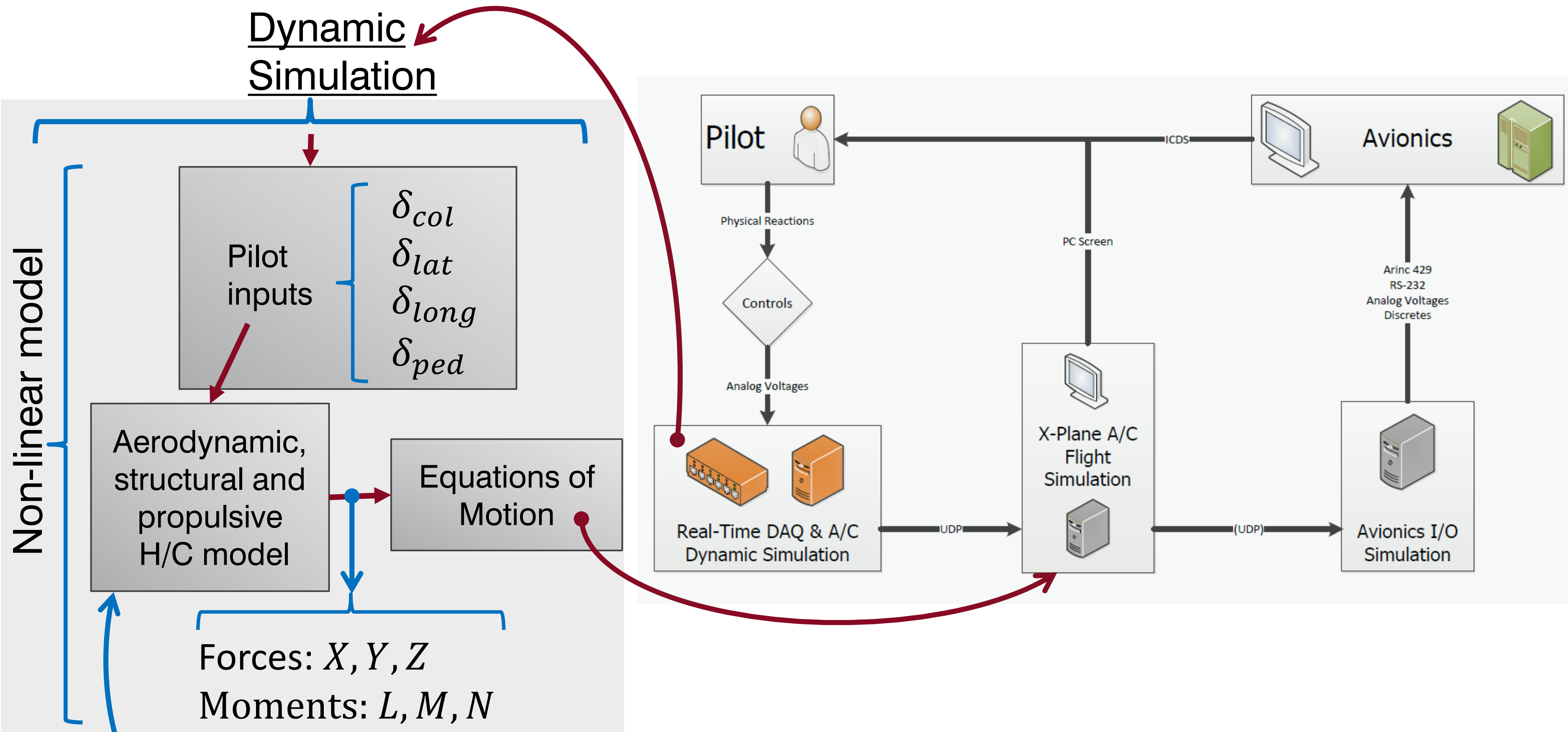
$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$



Suitable for:

- ➡ FCS design
- ➡ H/C flight simulation
- ➡ Aircraft dynamic stability analysis

Aircraft Simulation – Aircraft SID approach



System ID provides an <u>accurate</u>, <u>simple</u> and <u>reliable</u> model of the H/C dynamics obtained from <u>real</u> flight test data of the <u>real</u> H/C

In the form of

- LUTs
- LPV model
- …

System ID R/C Model vs FlightLab

H/C model from System ID

Advantages:

- High accuracy provided that good quality data points are available
- Validation -> instantaneous
- Non-linear flight dynamics
- Transient flight conditions
- Real-time dynamic modelling
- Account for aeroelastic effects

Drawbacks:

- Depend on flight test data availability and dedicated flight manoeuvres

Best use: Dynamic model of the real H/C:

- FCS design

- Handling qualities

- Simulator development

FlightLab H/C model

Advantages:

- Not dependent on flight test data
- Model complexity adjustable:
  Full aeroelastic -> loads&dynamics
  Rigid -> flight mechanics

Drawbacks:

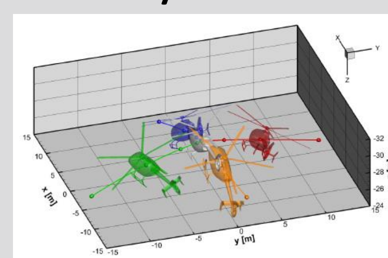
- Validation -> complicated
- Full aeroelastic model -> complicated
- Internal parameters hard to properly be tuned

Best use: Prediction of H/C:

- H/C and compnt. loads

- Rotor dynamics

- H/C Performance



How does it work?

Forces and moments

$$\frac{d}{dt}(mV) = \sum F = F_{Aero} + F_{Thrust} + F_{Gravity} + F_{Controls} + F_{Propulsion} + F_{Disturbances}$$

$$\frac{d}{dt}(Iw) = \sum M = M_{Aero} + M_{Thrust} + M_{Controls} + M_{Propulsion} + M_{Disturbances}$$

$\left.\begin{matrix}\sum F \\ \sum M\end{matrix}\right\}$ Develop a model form from which parameters can be estimated using <u>flight test data</u>

for example

Pitching moment coefficient

$$C_m = \underbrace{C_{m_0}}_{\text{pitching moment bias}} + \underbrace{C_{m_\alpha}}_{\text{static stability}} \overbrace{\alpha}^{\text{H/C angle of attack}} + \underbrace{C_{m_q}}_{\text{dynamic stability (damping)}} \overbrace{q}^{\text{longitudinal angular velocity}} + \underbrace{C_{m_\delta}}_{\text{pitch control authority}} \overbrace{\delta}^{\text{pitch control input}} + \cdots + \overbrace{\nu_m}^{\text{measurement noise}}$$

How does it work?

Pitching moment model:

$$\underbrace{C_m}_{} = \underbrace{C_{m_0}}_{} + \underbrace{C_{m_\alpha}}_{}\alpha + \underbrace{C_{m_q}}_{}q + \underbrace{C_{m_\delta}}_{}\delta + \nu_m$$

$$\theta = \left[C_{m_0}, C_{m_\alpha}, C_{m_q}, C_{m_\delta} \right]'$$

Vector of regressors (parameters to be identified)

Observations z

y: Model output
θ: Regresors
X: Values of variables measured
z: Observations
ν: Noise of the measurement

SID Model:

$$\begin{Bmatrix} y = \boldsymbol{X}\,\boldsymbol{\theta} \\ z = \boldsymbol{X}\,\boldsymbol{\theta} + \boldsymbol{\nu} \end{Bmatrix}$$

$$\hat{\theta}$$

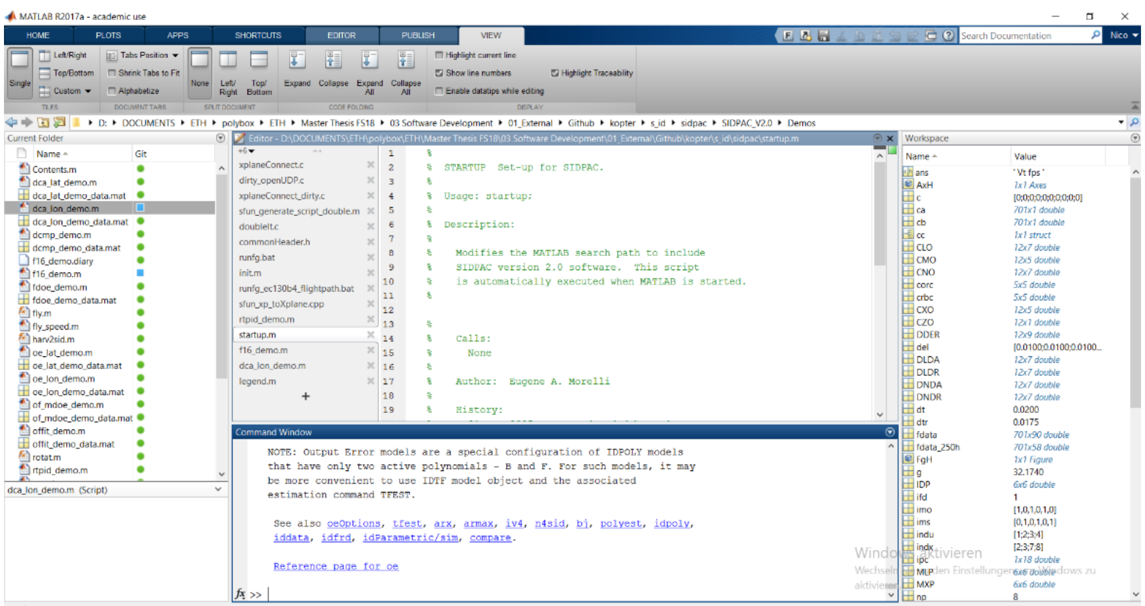
Equation-Error → Solved in one-shot linear algebra
- Simple
- Real time parameters estimations

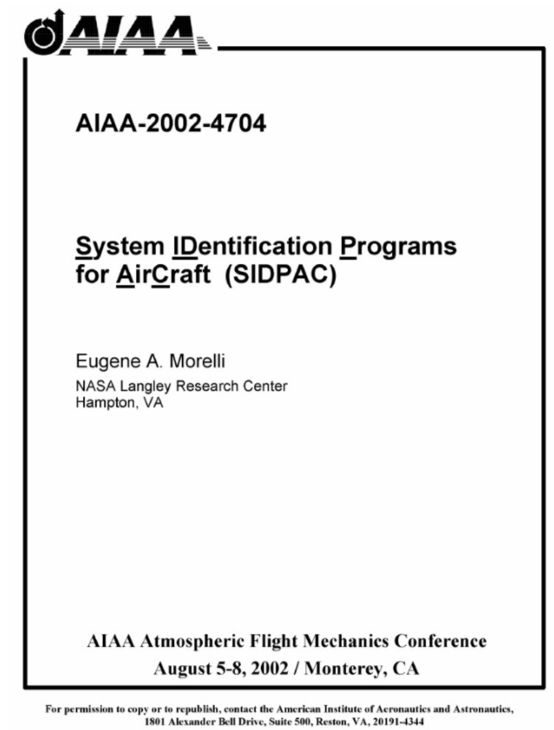
two approaches

Output-Error → Solved with iterative nonlinear optimization
- Any nonlinear system dynamics
- Machine learning techniques

Tools – SIDPAC software

- Implemented in Matlab
- Collection of over 350 state-of-the-art programs
- Used at more than 80 organization worldwide
- <u>No development time needed</u>




AIAA

AIAA-2002-4704

System IDentification Programs for AirCraft (SIDPAC)

Eugene A. Morelli
NASA Langley Research Center
Hampton, VA

AIAA Atmospheric Flight Mechanics Conference
August 5-8, 2002 / Monterey, CA

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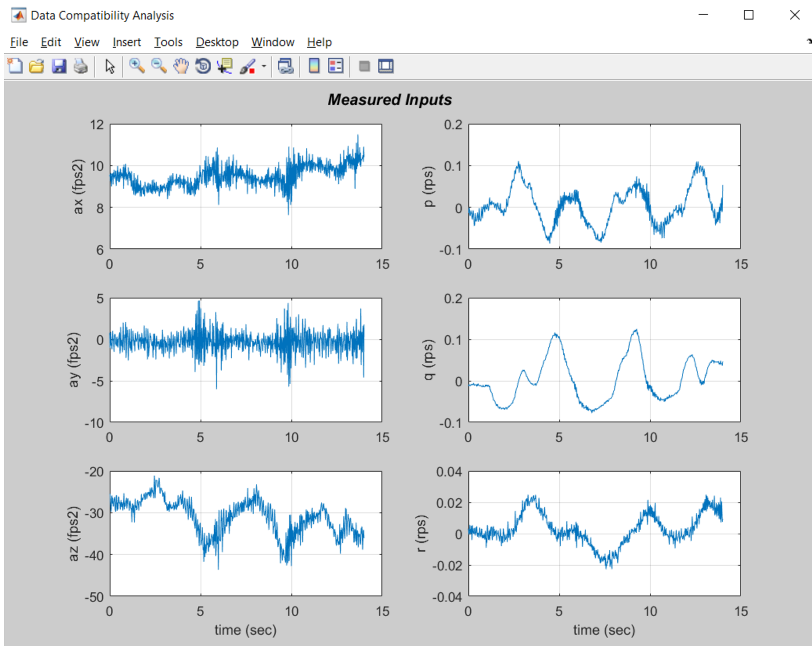
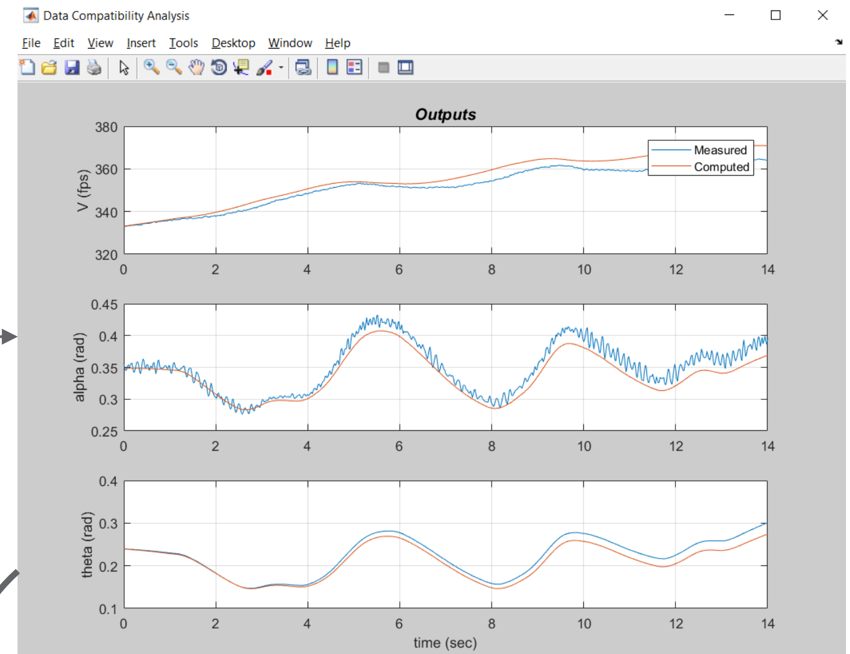
Tools – SIDPAC software



SID H/C Model



Measured inputs:

- a_x, a_y, a_z
- p, q, r

Outputs to be validated against <u>real</u> flight test data:

- V, α, θ

What would we need?

- Complete instrumented helicopter

- IMUs
- MR/TR rpm
- $\delta_{col}, \delta_{lat}, \delta_{long}, \delta ped$
- …

We already have this

- A laptop

- Some coffee…

Instrumentation overview

Table 9.1 Instrumentation characteristics for a general aviation airplane

Measured quantity	Transducer	Working range	Resolution	rms measurement error
a_x, g	Accelerometer	$[-1,1]$	0.001	0.0046
a_y, g	Accelerometer	$[-1,1]$	0.001	0.0050
a_z, g	Accelerometer	$[-3,6]$	0.001	0.0050
p, deg/s	Rate gyro	$[-102,102]$	0.12	0.20
q, deg/s	Rate gyro	$[-29,29]$	0.032	0.19
r, deg/s	Rate gyro	$[-29,29]$	0.034	0.080
ϕ, deg	Vertical gyro	$[-90,90]$	0.10	0.077
θ, deg	Vertical gyro	$[-87,87]$	0.098	0.092
α, deg	Flow vane	$[-12,27]$	0.029	0.027
β, deg	Flow vane	$[-29,32]$	0.018	0.019
δ_{a_r}, deg	Potentiometer	$[-23,10]$	0.002	0.019
δ_{a_l}, deg	Potentiometer	$[-10,25]$	0.002	0.0061
δ_s, deg	Potentiometer	$[-16,3]$	0.010	0.0037
δ_r, deg	Potentiometer	$[-31,28]$	0.011	0.0091
V, m/s	Pressure transducer	$[0,75]$	0.037	0.89
h, m	Altimeter	$[-150,2900]$	——	——
T, °C	Thermometer	$[-18,38]$	——	——

Table 9.2 Dynamic characteristics of transducers

Measured quantity	Transducer	Natural frequency, Hz	Damping ratio	Time delay, s
a_x, g	Accelerometer	402	1.58	0.0012
a_y, g	Accelerometer	216	1.10	0.0016
a_z, g	Accelerometer	921	1.58	0.0005
p, deg/s	Rate gyro	27	0.64	0.0075
q, deg/s	Rate gyro	27	0.64	0.0075
r, deg/s	Rate gyro	27	0.64	0.0075
α, deg	Flow vane	23[a]	0.085[a]	0.0012
β, deg	Flow vane	23[a]	0.085[a]	0.0012

[a] At $V = 164$ ft/s

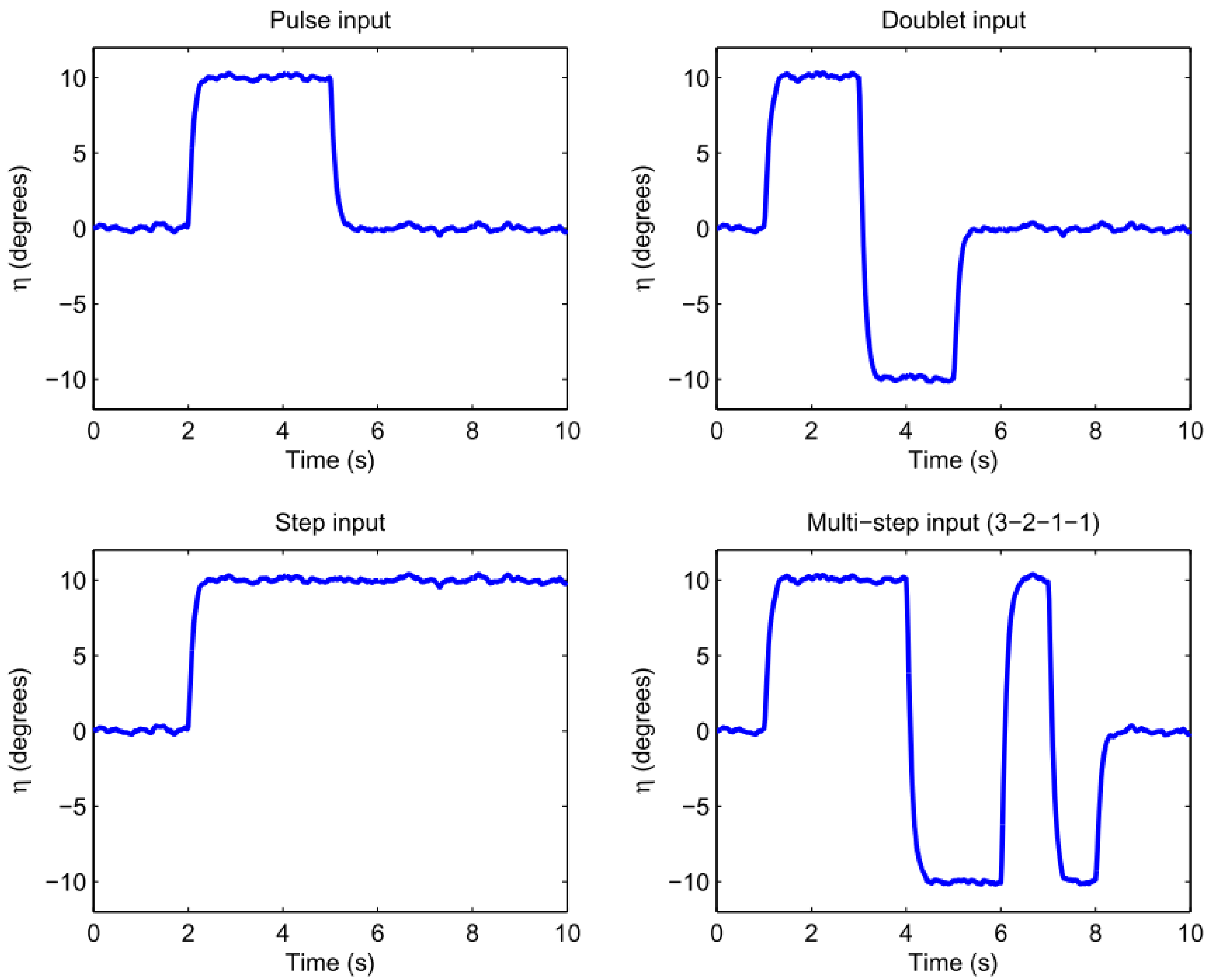
Inputs

Constraints on inputs:

- Rate of data acquisition
- Limited resolution on sensors or data acquisition system

- Limited time for each maneuver
- Limitations on how the aircraft can be excited

Inputs



Pulse input
Doublet input
Step input
Multi−step input (3−2−1−1)
η (degrees)
Time (s)
10
5
0
−5
−10
0
2
4
6
8
10

Why to introduce System ID into P3 test campaign?

kopter

- Sooner or later, it would need to be implemented → Every big helicopter manufacturer has a dedicated SID department
- SID framework could be developed now using P2 flight test data
- Assist P3 flight envelope expansion in Sicily, necessary for TC. Issues like the cyclic migration could be addressed and main driving parameters identified.
- Provide a proper dynamic model of the H/C for the simulator
- Surely it will be needed for PS4 and further developments after TC, such as FCS design
- Cost effective

We have to do it now, we are ready now

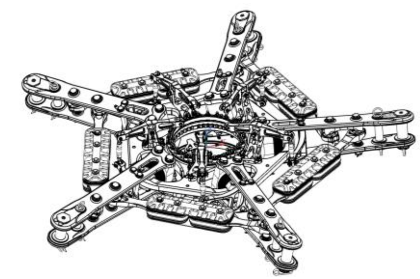
System ID takes time and money – but not nearly as much as not doing it

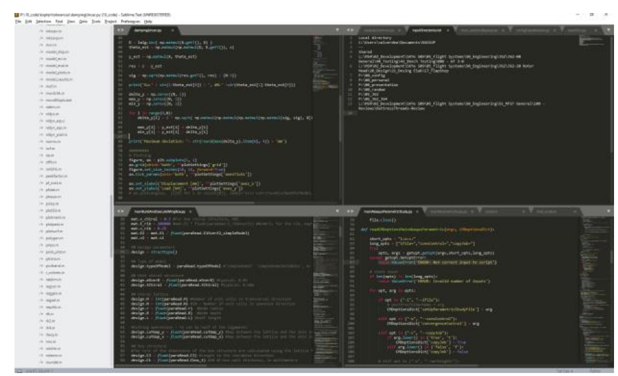
Eugene A. Morelli
NASA Langley Research Center Hampton

Why I can be the one doing this?

Young *Passionate*

- I know what to do and how to do it
- Kopter experience, within rotorheads
- Data analysis experience
  - Python
  - Matlab
  - Data analysis and machine learning techniques
  - …
- Availability from April onwards





Next steps – Near future

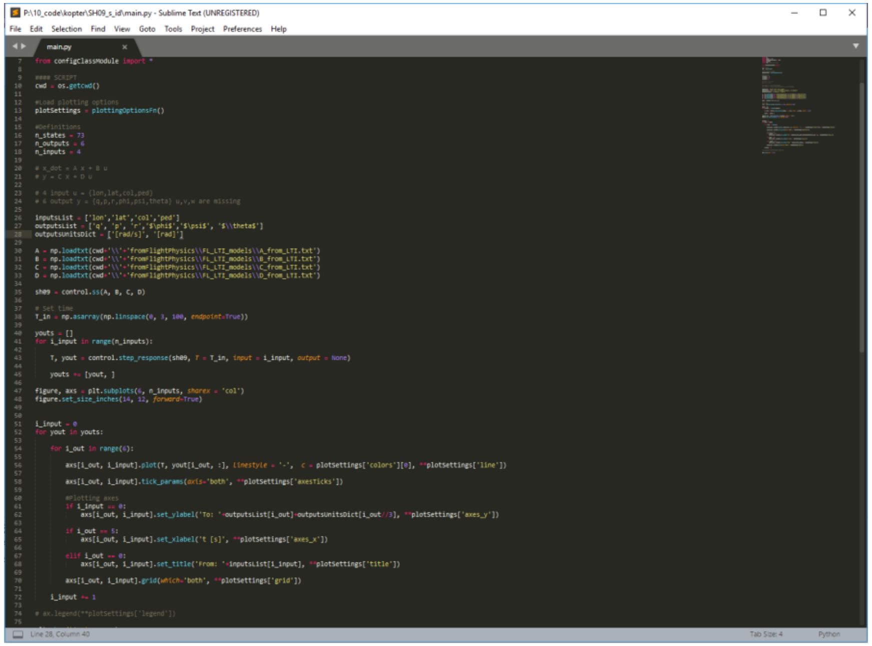
- Perform first approach System ID on FlightLab:
  - Rigid body System ID framework
  - FlightLab linearized model
  - Inclusion of simulated disturbances in the measurements
- Develop a System ID framework suitable for real flight test data:
  - Rigid body System ID framework
  - Use of P2 flight test data if suitable
  - Assessment of handling qualities issues
  - Inclusion of aeroelastic effects
  - Provide dynamic model of P2 suitable for:
    - FCS design
    - Simulator development

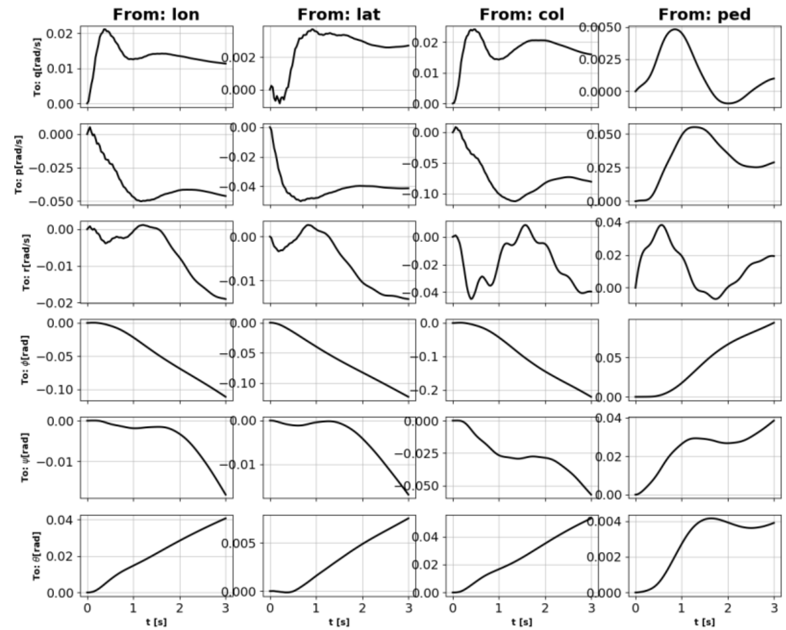
April → Beginning of summer

- Assist P3 flight envelope expansion in Sicily:
  - Developed System ID framework could be ready to:
    - Perform post-flight analysis for accurate parameter estimation
    - Real-time dynamic modelling
  - Address handling qualities issues

Beginning of summer → …

First steps, using FlightLab





- fwd level flight
- 147 kts
- 2800 kg
- x_{cg} = 3.37m

<u>LTI model</u>

$$y = \boldsymbol{X}\,\boldsymbol{\theta}$$
$$z = \boldsymbol{X}\,\boldsymbol{\theta} + \boldsymbol{\nu}$$

- 73 states
- 6 outputs
- 4 inputs


SH09
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Thank you

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References

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[2] R. K. Remple and M. B. Tischler, *Aircraft and Rotorcraft System Identification*. 2006.

[3] G. Morelli and S. Derry, "System Identification Methods for Aerodynamic Modeling and Validation using Flight Data," 2011.

[4] G. Morelli, "Aircraft System Identification," 2011.

System ID methodology diagram