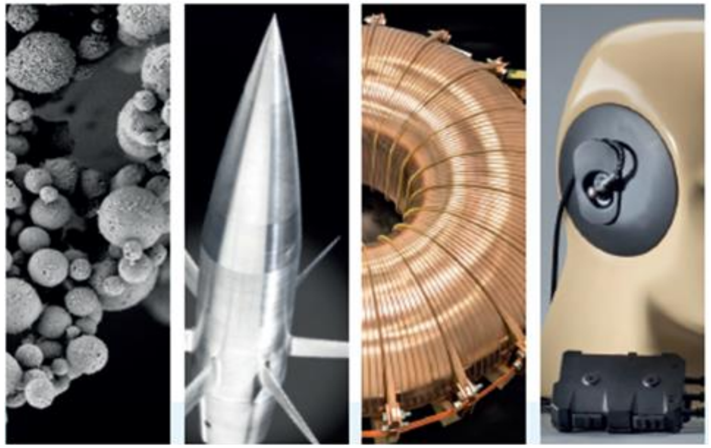

Terminal phase nonlinear attitude autopilot design

for dual-spin guided projectiles

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A joint initiative of

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Outline

- ❑ **General context & motivation**

- ❑ **Flight dynamics modelling & nonlinear simulator**

- ❑ **Nonlinear flight control**
  - Incremental Nonlinear Dynamic Inversion (INDI)
  - Nonlinear autopilot design methodology

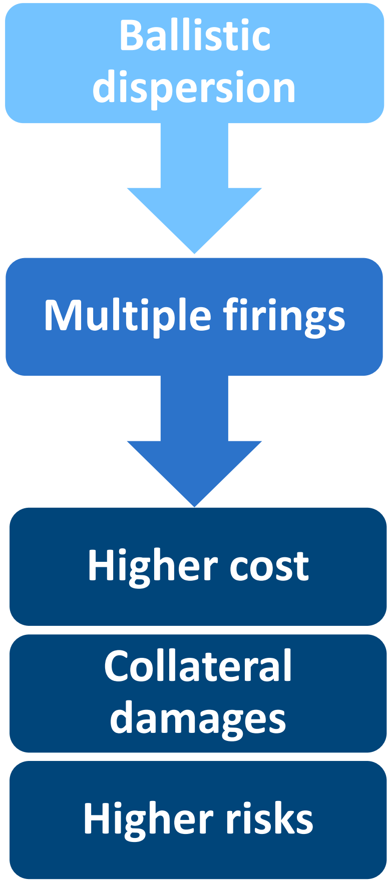
- ❑ **Design & nonlinear simulations results**
  - Roll autopilot design
  - Lateral channels (Pitch/yaw rate) decoupling
  - Terminal phase attitude autopilot

- ❑ **Conclusion & Future work**

General context

Existing technology

Fig.1: *Standard 155 mm ammunition*



Ballistic dispersion

Multiple firings

Higher cost

Collateral damages

Higher risks

ISL solution

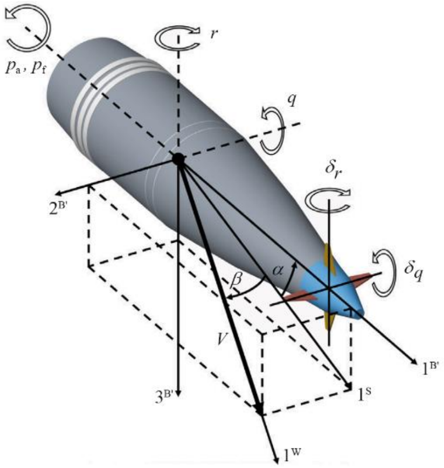
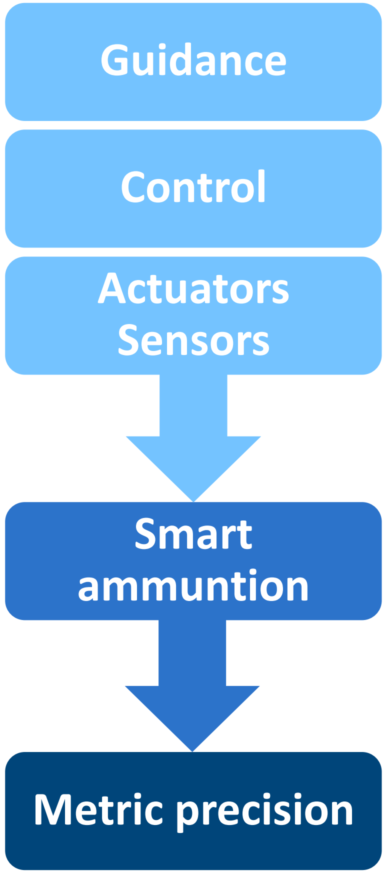


Fig.2: *ISL Decoupled Fuse Guided Projectile (DFGP)*



Guidance

Control

Actuators Sensors

Smart ammuntion

Metric precision

Previous work & Legacy control strategy

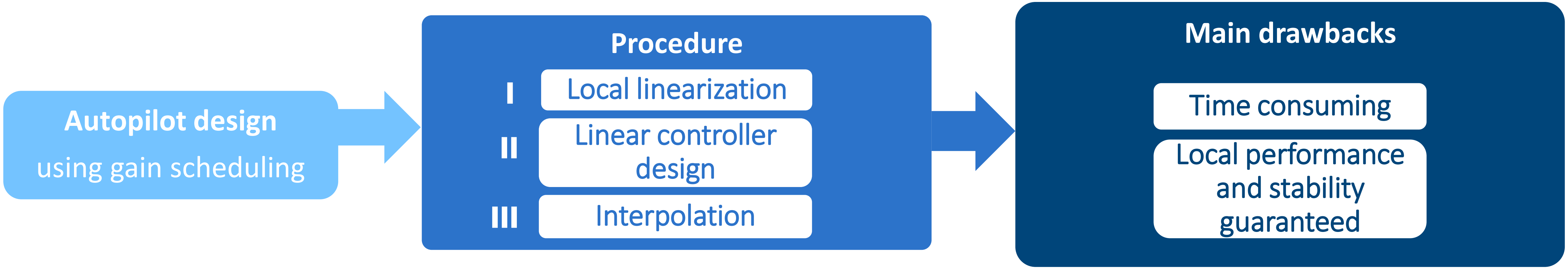
Publications:

S. Theodoulis, F. Sève and P. Wernert, Robust Gain-Scheduled Autopilot Design for Spin-Stabilized Projectiles with a Course-Correction Fuze, *Aerospace Science and Technology* (AST), 42(1) : 477-489, April-May 2015.

F. Sève, S. Theodoulis, P. Wernert, M. Zasadzinski, and M. Boutayeb, Gain-Scheduled $\mathcal{H}_\infty$ Loop-Shaping Autopilot Design for Spin-Stabilized Canard-Guided Projectiles, *Aerospace Lab – Special issue on design & validation of aerospace control systems*, 2017.

F. Sève, S. Theodoulis, P. Wernert, M. Zasadzinski, and M. Boutayeb, Flight Dynamics Modeling of Dual-Spin Guided projectiles, *IEEE Transactions on Aerospace and Electronic Systems*, 2017.

S. Thai, S. Theodoulis, C. Roos, J.M. Biannic and M. Proff. Gain-Scheduled Autopilot Design with Anti-Windup Compensator for a Dual-Spin Canard-Guided Projectile, *IEEE Conference on Control Technology and Applications*, 2020.



Autopilot design

using gain scheduling

Procedure

- I Local linearization
- II Linear controller design
- III Interpolation

Main drawbacks

- Time consuming
- Local performance and stability guaranteed

Fig.3: *Gain-scheduling approach for autopilot design*

Motivation for a nonlinear autopilot design methodology

☐ Need for a methodology dedicated to **fast** and **generic** design of autopilots keeping **performance and stability** across **all** flight envelope:

- Rapid design
  - Use of **Incremental Nonlinear Dynamic Inversion** (INDI)[1-3] which requires the tuning of a unique linear controller to cover all flight envelope.
- Generic prototyping
  - Development of Matlab/Simulink **SMART* toolbox** providing accurate flight dynamics modeling for **trajectory simulation & autopilot validation.**

*System Modelling Ammunition Research Tools

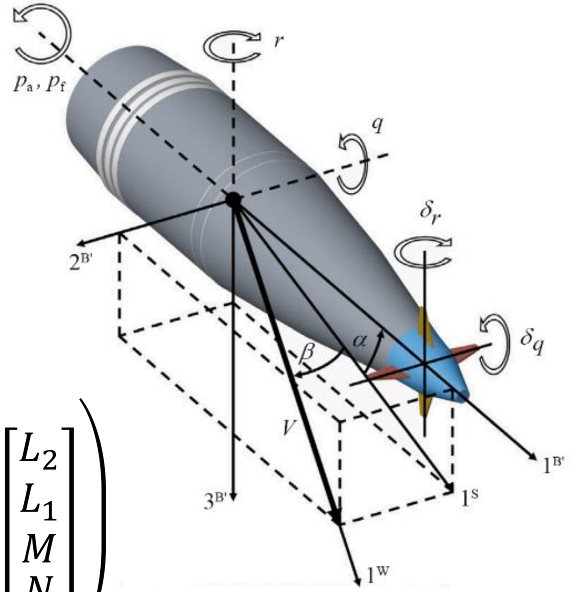
- Performance and stability
  - Implementation constraints such as **potential on-board delays** and **computational sampling time** were integrated into the design process associated with $\mathcal{H}_\infty$ robust control theory.

[1]P. Smith. A simplified approach to nonlinear dynamic inversion based flight control. *23rd Atmospheric Flight Mechanics Conference*. American Institute of Aeronautics and Astronautics, August 1998.

[2] B.J. Bacon, A.J. Ostroff, and S.M. Joshi. Reconfigurable NDI controller using inertial sensor failure detection & isolation. *IEEE Transactions on Aerospace and Electronic Systems*, 37(4):1373–1383, 2001.

[3] S. Sieberling, Q. P. Chu, and J. A. Mulder. Robust flight control using incremental nonlinear dynamic inversion and angular acceleration prediction. *Journal of Guidance, Control, and Dynamics*, 33(6):1732–1742, November 2010.

Flight Dynamics modelling



- ☐ **Translation** and **attitude** dynamics equations:

$$\begin{bmatrix}\dot{u}\\ \dot{v}\\ \dot{w}\end{bmatrix} = \left(\frac{1}{m^{\mathrm{B}}}\right)\begin{bmatrix}X\\ Y\\ Z\end{bmatrix} - \begin{bmatrix}0 & -r & q\\ r & 0 & r\tan\theta\\ -q & -r\tan\theta & 0\end{bmatrix}\begin{bmatrix}u\\ v\\ w\end{bmatrix}$$

$$\begin{bmatrix}\dot{p}_2\\ \dot{p}_1\\ \dot{q}\\ \dot{r}\end{bmatrix} = \begin{bmatrix}I_{x_2}^{-1} & 0 & 0 & 0\\ 0 & \tilde{I}_{x_1}^{-1} & 0 & 0\\ 0 & 0 & \tilde{I}_t^{-1} & 0\\ 0 & 0 & 0 & \tilde{I}_t^{-1}\end{bmatrix}\left(\begin{bmatrix}0 & 0 & 0 & 0\\ 0 & 0 & r & -q\\ 0 & -r & 0 & -r\tan\theta\\ 0 & q & r\tan\theta & 0\end{bmatrix}\begin{bmatrix}I_{x_2} & 0 & 0 & 0\\ 0 & \tilde{I}_{x_1} & 0 & 0\\ 0 & 0 & \tilde{I}_{x_1} & 0\\ 0 & 0 & 0 & \tilde{I}_{x_1}\end{bmatrix}\begin{bmatrix}p_2\\ p_1\\ q\\ r\end{bmatrix} + \begin{bmatrix}L_2\\ L_1\\ M\\ N\end{bmatrix}\right)$$

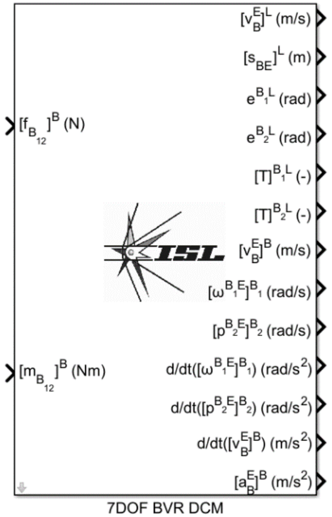


Fig.4: *SMART toolbox Matlab/Simulink blockset*

- ☐ The SMART toolbox includes all necessary blockset for 7DoF flight dynamics modelling:
  - Equations of motion
  - Forces & moments
  - Actuators & sensors
  - Environment modelling

- ☐ SMART toolbox key features:
  - **Unified notation** befitting modern flight dynamics
  - Easier change of initial conditions and parameters
  - More **flexible** modelling environment

Nonlinear flight control: Incremental Nonlinear Dynamic Inversion

- ❑Inversion-based autopilot structured in an **inner/outer loop** configuration:
  - **Inner loop:** inverts and linearizes the plant dynamics which then act like a chain of integrators.
  - **Outer loop**: sets the desired closed-loop behavior with an external linear controller.

- ❑Incremental Nonlinear Dynamic Inversion (INDI) was used to linearize and decouple roll and lateral dynamics.
  - **Sensor-based approach**: less dependent than classical NDI[4] to model mismatch and more robust to disturbances and uncertainties [5].
  - **Fast actuators** and **non-biased sensors** are required for inversion.

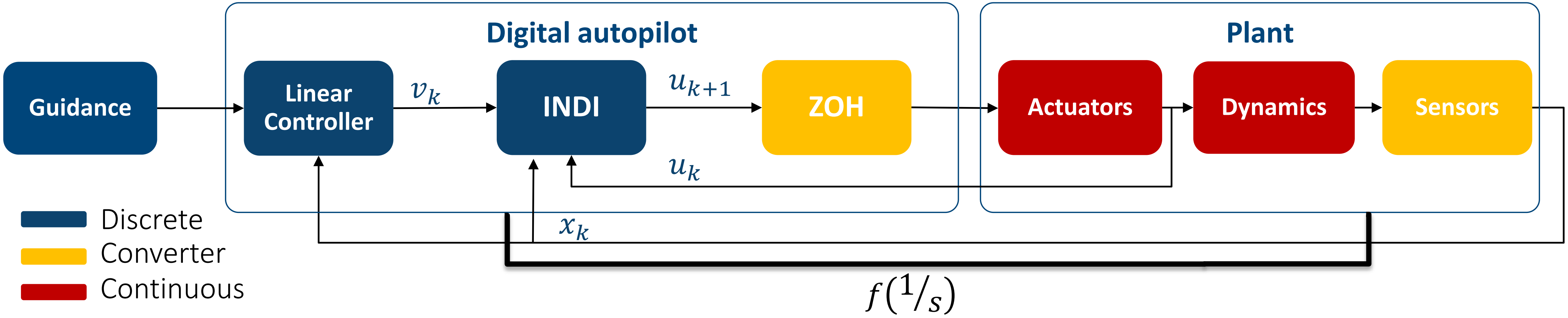


Fig.5: *INDI digital autopilote architecture*

[4]Tipán, Steven & Thai, Sovanna & Proff, Michael & Theodoulis, Spilios. (2020). Nonlinear Dynamic Inversion Autopilot Design for Dual-Spin Guided Projectiles. IFAC

[5] Wang, E-J. van Kampen, Q-P. Chu, and P. Lu. Stability Analysis for Incremental Nonlinear Dynamic Inversion Control. *Journal of Guidance, Control, and Dynamics*, 42(5):1116–1129, May 2019

Nonlinear flight control: INDI theory

Considering the following nonlinear system:

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

The objective is **to invert and impose the dynamic** as:

$$\dot{x} = v$$

Inversion of the plant using control signal *u*:

$$\dot{x} = f(x, u) \approx f(x_0, u_0) + \frac{df}{dx}(x - x_0) + \frac{df}{du}(u - u_0)$$

$$\dot{x} \approx f(x_0, u_0) + F\Delta x + G\Delta u = v$$

Considering **time-scale separation** we have $\Delta x \ll \Delta u$:

$$\dot{x} \quad \approx \dot{x}_0 + G\Delta u = v$$

$$\Delta u = G^{-1}[v - \dot{x}_0]$$

With discrete time INDI :

$$\Delta u \approx u_k - u_{k-1}$$

$$\dot{x}_k \approx \frac{x_k - x_{k-1}}{T}$$

Thus u_{k+1} is expressed as following

$$\boxed{u_{k+1} = u_k + G^{-1}\left(v_k - \frac{x_k - x_{k-1}}{T}\right)}$$

Nomenclature:

x_0: last state measurement
v : pseudo-control variable
G : control effectiveness matrix
T : sampling period
u : control signal

Considerations about INDI:

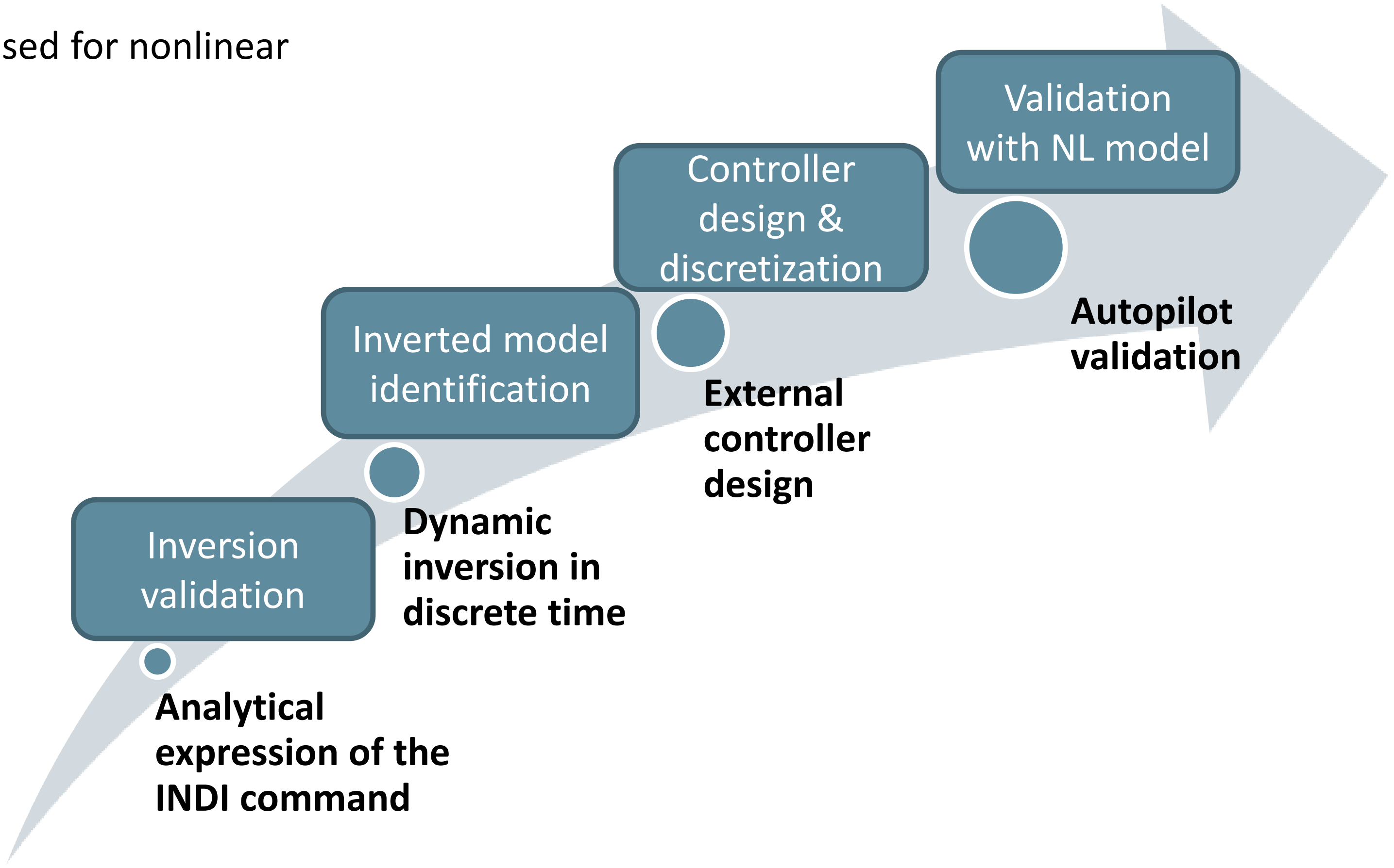
- ☐ Only model parameters related to control effectiveness (G) are needed for inversion.
- ☐ Actuators dynamics is considered very fast compared to state dynamics.
- ☐ State derivative $\dot{x}_k$ needs to be measured or estimated (Euler backward method).

Nonlinear flight control : Nonlinear autopilot design methodology

- A **systematic** and **straightforward** methodology is proposed for nonlinear autopilot design using **inversion based control laws.**

- Autopilot validation performed with several models:
  1. Controller only with inverted model
  2. Controller+ INDI with NL model for 1 flight point
  3. Full autopilot with nonlinear model

- This methodology has been applied for the design of a terminal phase angle autopilot which requires:
  - Stabilization of fuse roll angle
  - Lateral channels rate decoupling
  - Control of pitch and yaw angles



Inversion validation

Analytical expression of the INDI command

Inverted model identification

Dynamic inversion in discrete time

Controller design & discretization

External controller design

Validation with NL model

Autopilot validation

Fig 6: *Inversion-based nonlinear autopilot design methodology*

Roll autopilot design

Roll dynamics

$$\left\{\begin{array}{c}\dot{\varphi}_2 = p_2\\ \dot{p}_2 = I_{x_2}^{-1}\left(\bar{q}SC_{l_\delta}\delta_p\right) + L_f\end{array}\right\}$$

INDI command

$$\delta_{p_{k+1}} = \delta_{p_k} + \frac{I_{x_2}}{\bar{q}SdC_{l_\delta}}\left(v_k - \frac{p_{2_k} - p_{2_{k-1}}}{T}\right)$$

Inverted dynamics model

$$\frac{\varphi_2(s)}{\varphi_{2_{cmd}}(s)} = \frac{1-\frac{T}{2}s}{s^2}$$

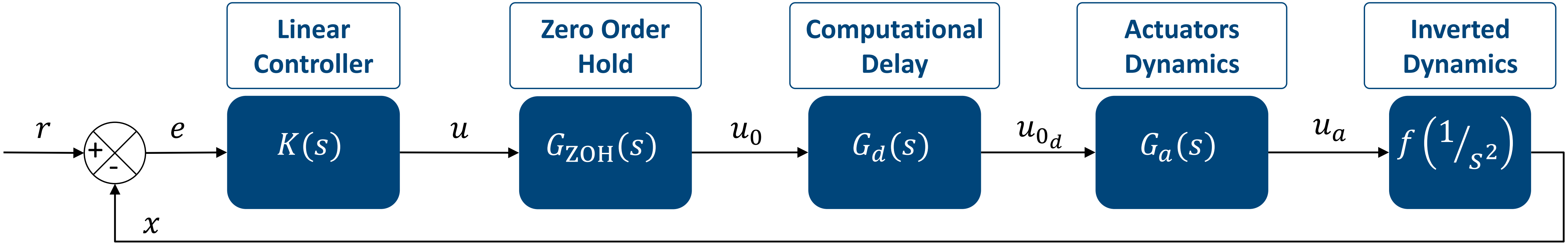


Fig.7 : *Modified continuous design layout*

- ❑ Design of the external controller in continuous time taking account of discrete time constraint via standard "**Modified continuous design**"[6].
- ❑ ZOH and computational delay transfer functions modeled by **Pade approximant**.

[6] Stevens, B and Lewis, F., *Aircraft Control and Simulation*, Wiley, Hoboken, New Jersey, 2015, pp. 609-619

Roll autopilot design: external controller tuning

- ☐ Multi-objective tuning with hard and soft constraints such as reference model following, disturbance rejection, phase and gain margins.

Hard Constraints	
Reference model following	$G_r(s) = \frac{\omega_r^2}{s^2+2\xi_r\omega_r s+\omega_r^2}$ • Max overshoot : 2% • Settle time : 0,3 s
I/O disturbance rejection	$S_{i/o} = \frac{\left(\frac{s}{\sqrt{M}} + \omega_b\right)^2}{\left(s + \omega_b\sqrt{A}\right)^2}$
Controller bandwidth reduction	Low pass filter

Soft Constraints	
Gain margin	$GM > 6 \text{ dB}$
Phase margin	$PM > 35\,°$

Fig.8: *Roll controller design objectives*

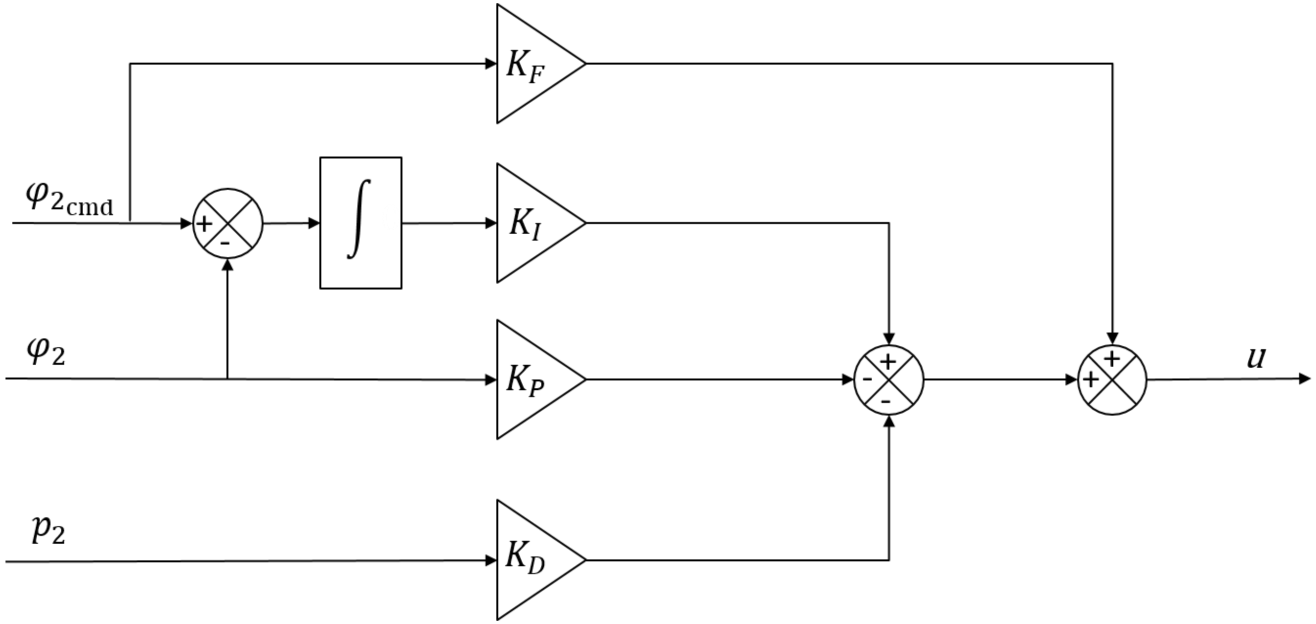


Fig.9: *Roll controller architecture*

- ☐ P-IPP controller structure with **feedforward/servo/regulator** parts.
- ☐ Multi-objective controller tuning made with **Matlab systune.**

Roll autopilot design: design results

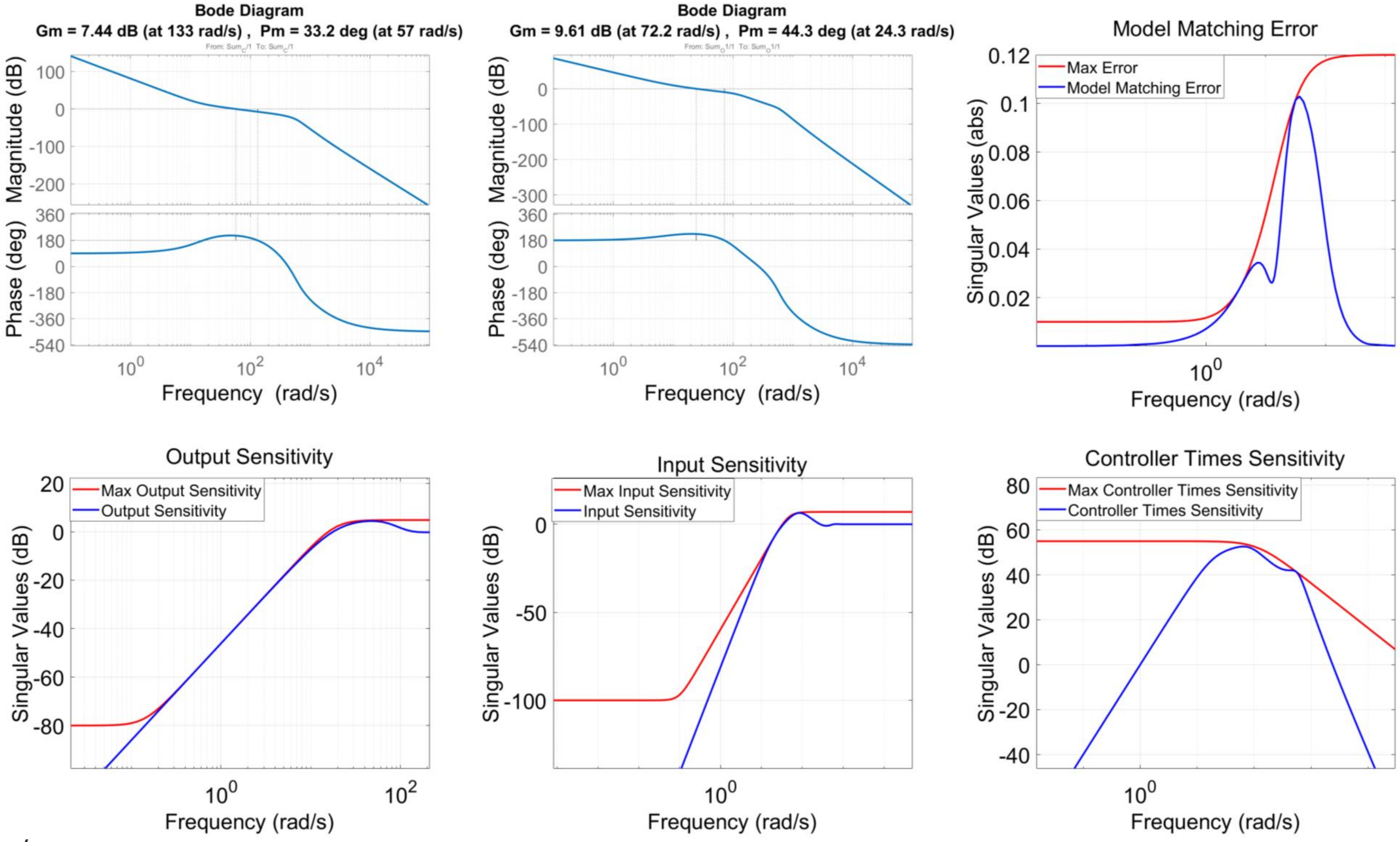


Fig.10: *Roll autopilot design frequency results*

- Very low model matching error in low frequency
- High constraint for sensitivity functions in high frequency
- Controller bandwidth reduced in low frequency
- Satisfactory delay margin $DM = 45$ ms

Roll autopilot design: simulation results

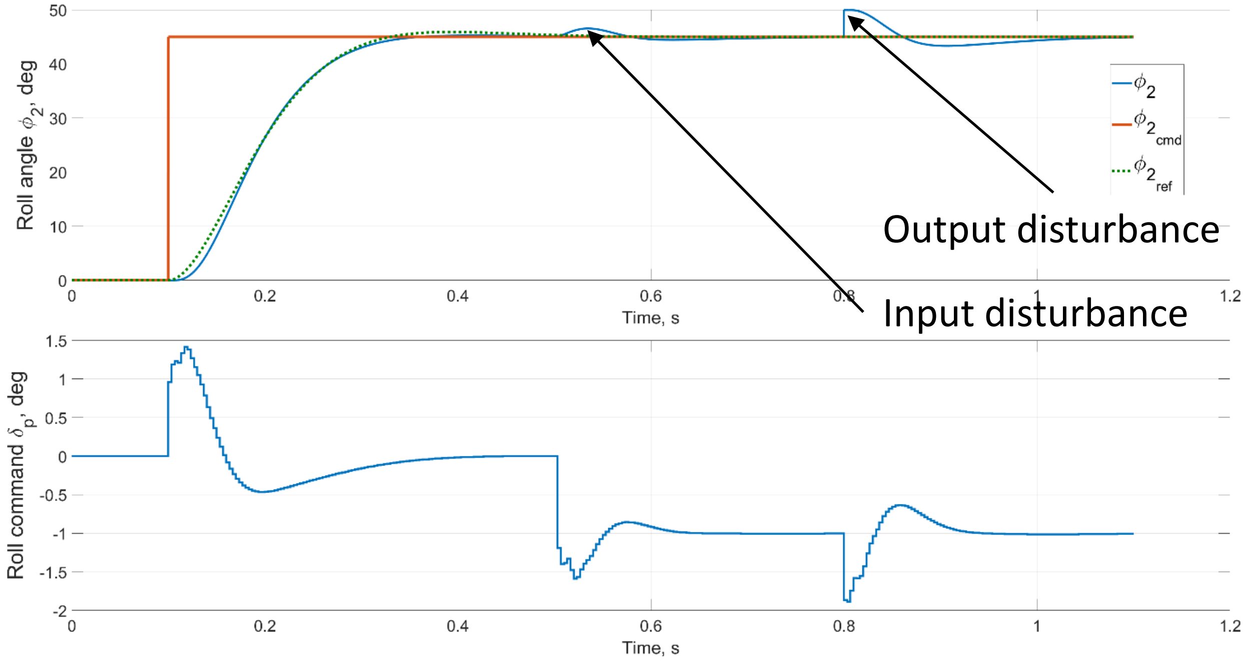


Fig.11: *Roll autopilot simulation for one flight point*

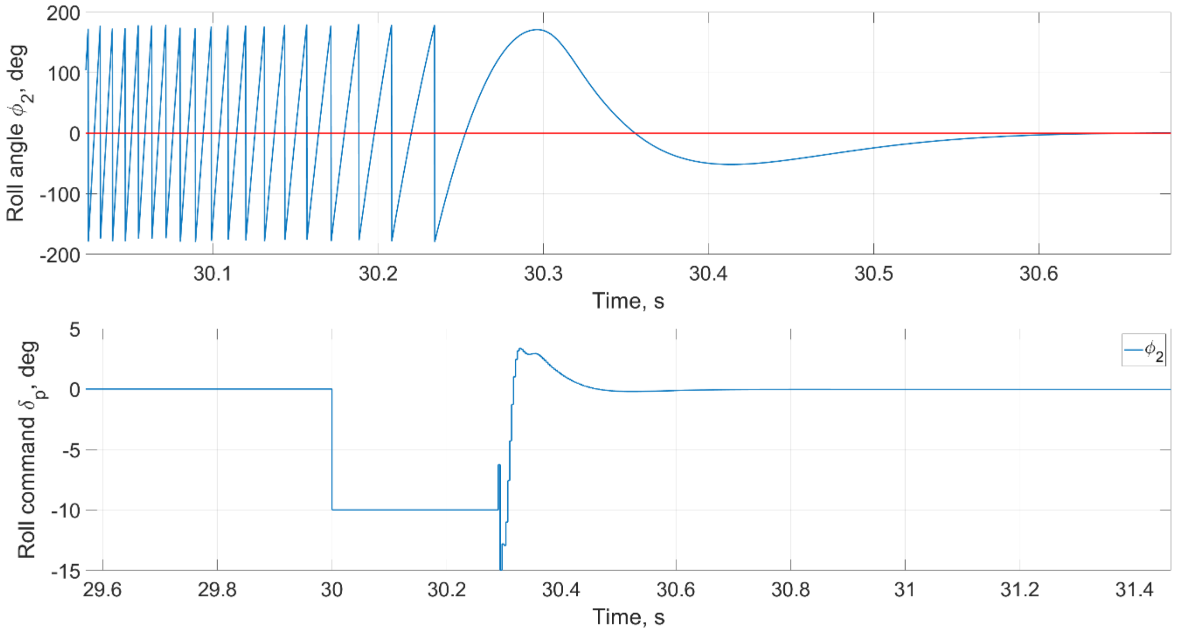


Fig.12: *Roll autopilot nonlinear simulation*

- ☐ **LTI model simulation**
  - Transient response very close to reference model.
  - Satisfactory I/O disturbance rejection.

- ☐ **Nonlinear simulation**
  - The fuse has a **high spin rate** due to friction with projectile aft part.
  - Fuse roll angle control strategy:
    - Spin rate reduction by putting all four canards into saturation.
    - Roll angle stabilization using roll autopilot.

Lateral channels decoupling

Pitch/Yaw rates dynamics

$$\begin{cases} \dot{q} = \dfrac{I_{x_1}}{I_t} p_1 r \; - r^2 \tan\theta + \left(\dfrac{\bar{q} S d}{I_t}\right) C_{m_\delta} \delta_q \\ \dot{r} = \dfrac{I_{x_1}}{I_t} p_1 q \; - qr \tan\theta + \left(\dfrac{\bar{q} S d}{I_t}\right) C_{m_\delta} \delta_r \end{cases}$$

INDI command

$$\begin{pmatrix} \delta_{q_{k+1}} \\ \delta_{r_{k+1}} \end{pmatrix} = \begin{pmatrix} \delta_{q_k} \\ \delta_{r_k} \end{pmatrix} + \begin{pmatrix} \dfrac{I_t}{\bar{q} S d C_{m_\delta}} & 0 \\ 0 & \dfrac{I_t}{\bar{q} S d C_{m_\delta}} \end{pmatrix} \begin{pmatrix} v_{q_k} - \dfrac{q_k - q_{k-1}}{T} \\ v_{r_k} - \dfrac{r_k - r_{k-1}}{T} \end{pmatrix}$$

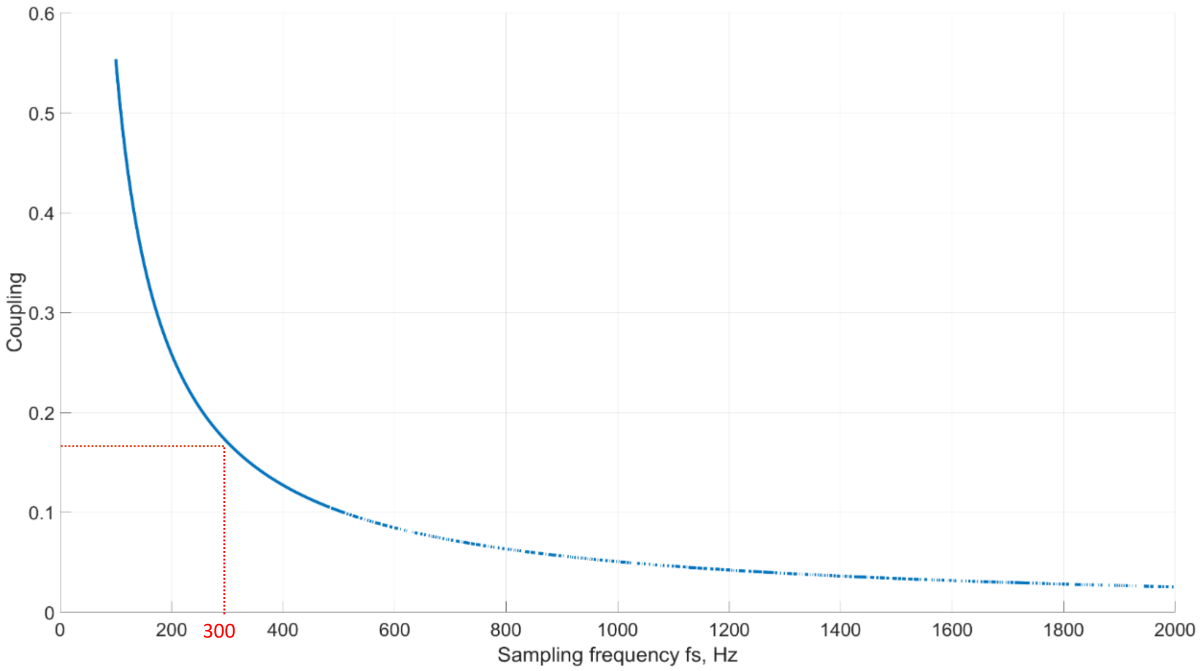


Fig.13: *Influence of the sampling frequency on INDI decoupling capacities for lateral channels*

- Lateral channels **not perfectly decoupled** with discrete time INDI.
- With $T = \frac{1}{300}$ s, remaining coupling is not negligible and needs to be included into the inverted dynamics model.
- Full order $\mathcal{H}_\infty$ controller used to fully decouple lateral channels.

Lateral channels decoupling: design results

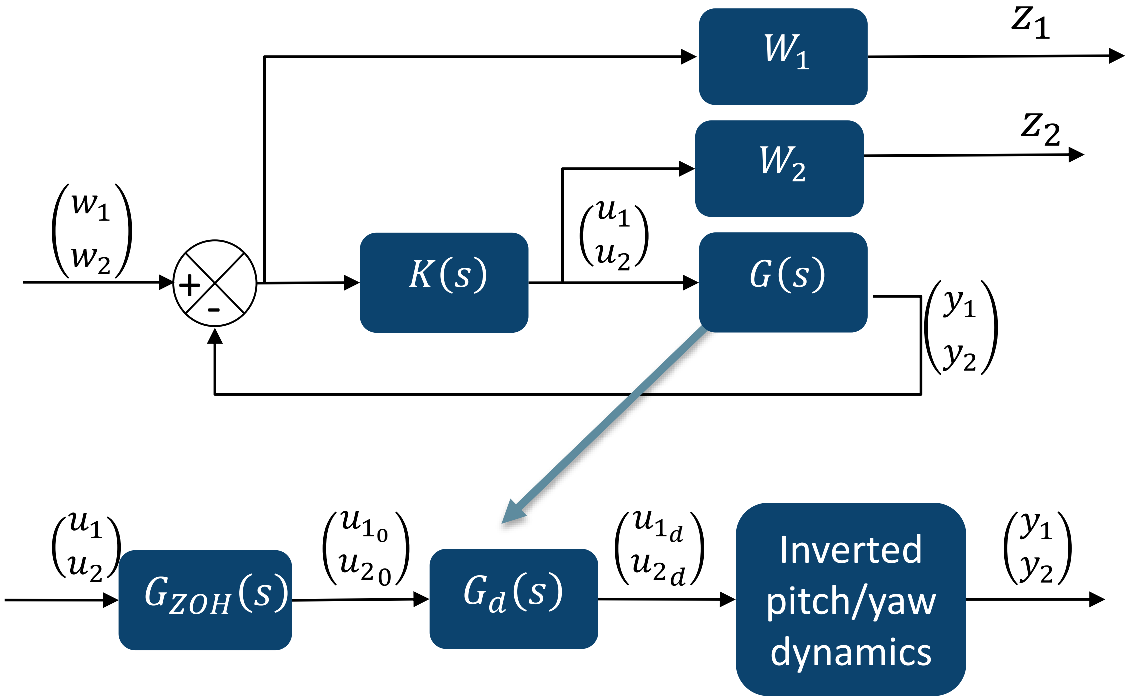


Fig.14: $\mathcal{H}_\infty$ mixed sensitivity augmented plant

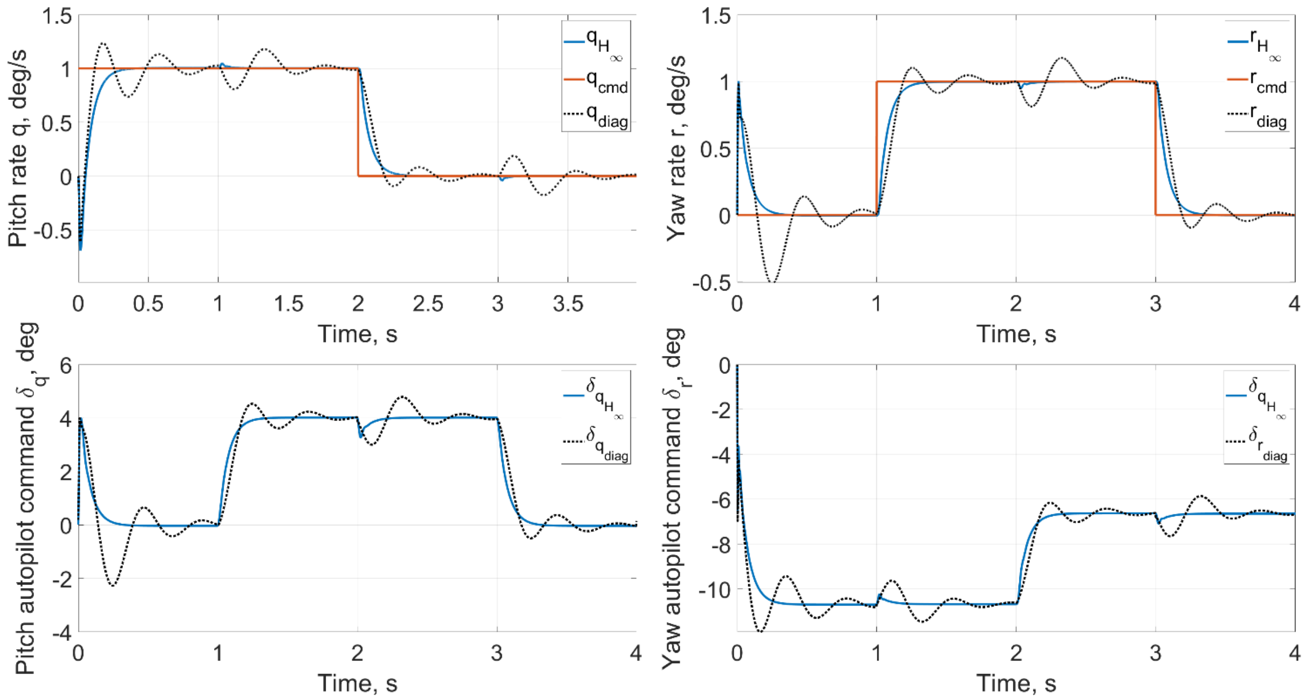


Fig.15: *Performance comparison between a diagonal controller and a $\mathcal{H}_\infty$ controller*

- ☐ Full order $\mathcal{H}_\infty$ external controller shows better performance and decoupling capacity than a diagonal controller.
- ☐ Pitch/yaw rate autopilot is then cascaded with a unique linear controller to control pitch and yaw angles in terminal flight phase.

Terminal phase attitude autopilot

☐ Full control of **impact angles** resulting in **increased target efficiency** in top attack (e.g. engagement of armored vehicle).

☐ **Classical** and **straightforward** design process using only a **unique** linear controller.

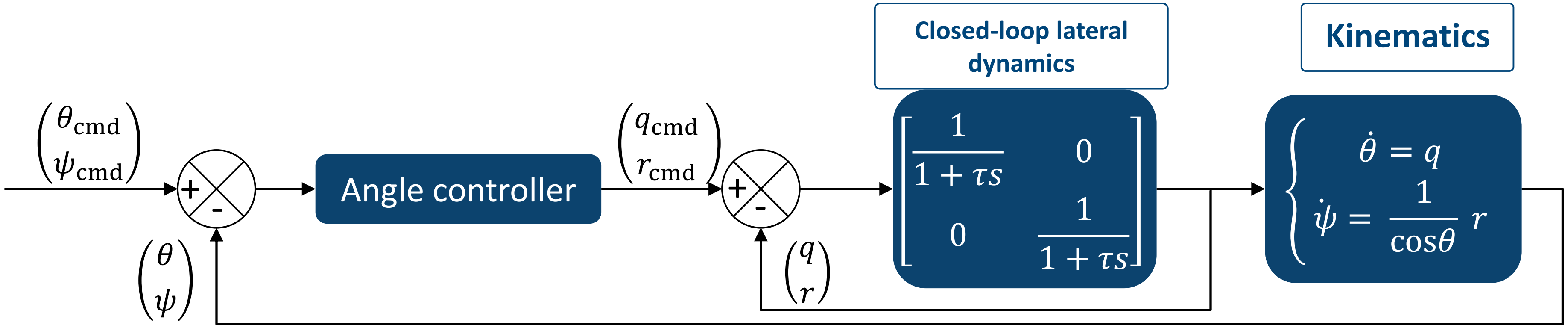


Fig.16: *Terminal phase attitude autopilot design model*

☐ Two simulation scenarios proposed:

- High pitch impact angle for top attack scenario.
- Reduced aerodynamic angle in terminal phase.

Terminal phase attitude autopilot: top attack scenario

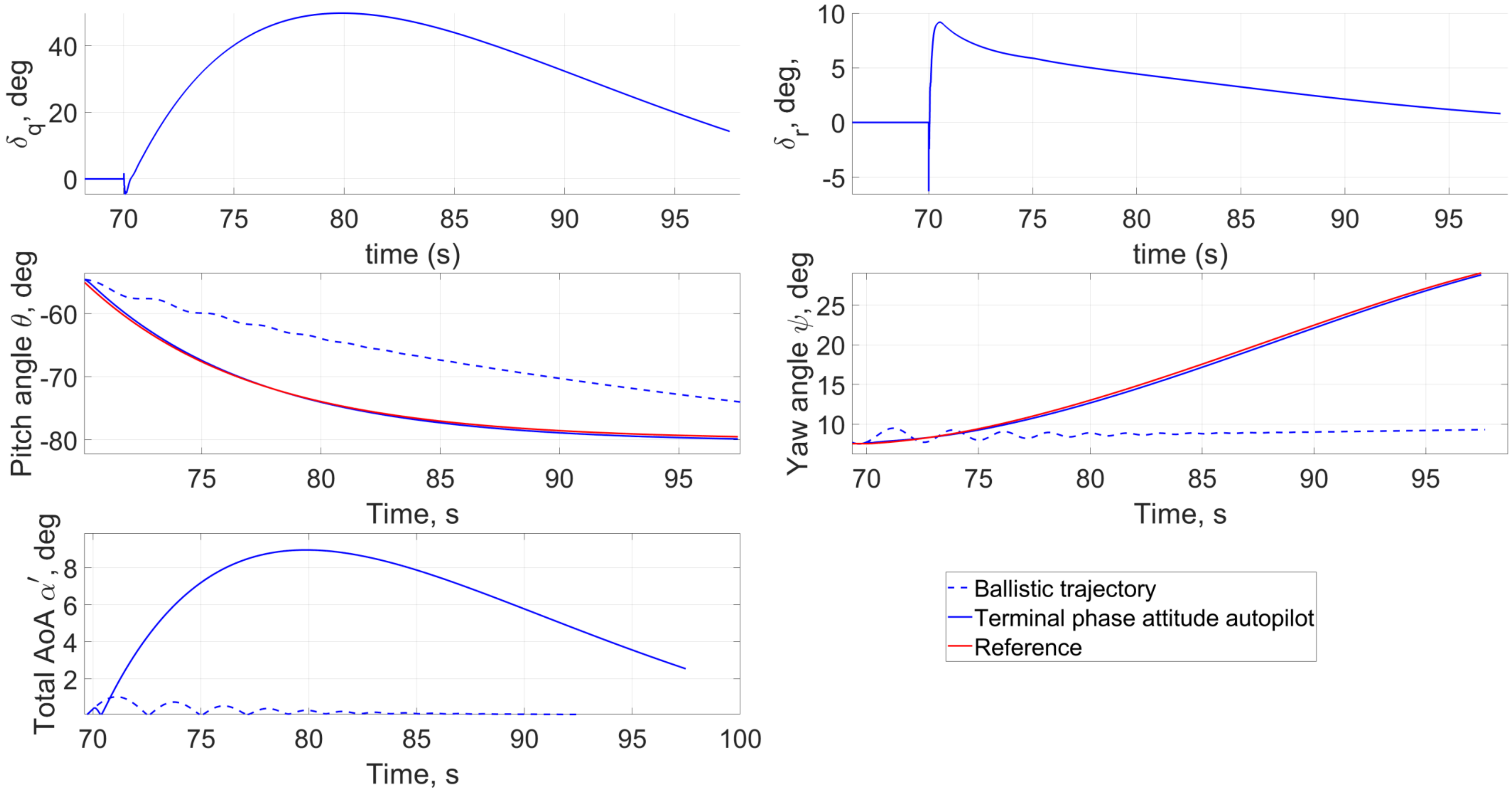


Fig.17: *Terminal phase attitude autopilot – Top attack scenario*

Terminal phase attitude autopilot: *reduced aerodynamic angle* scenario

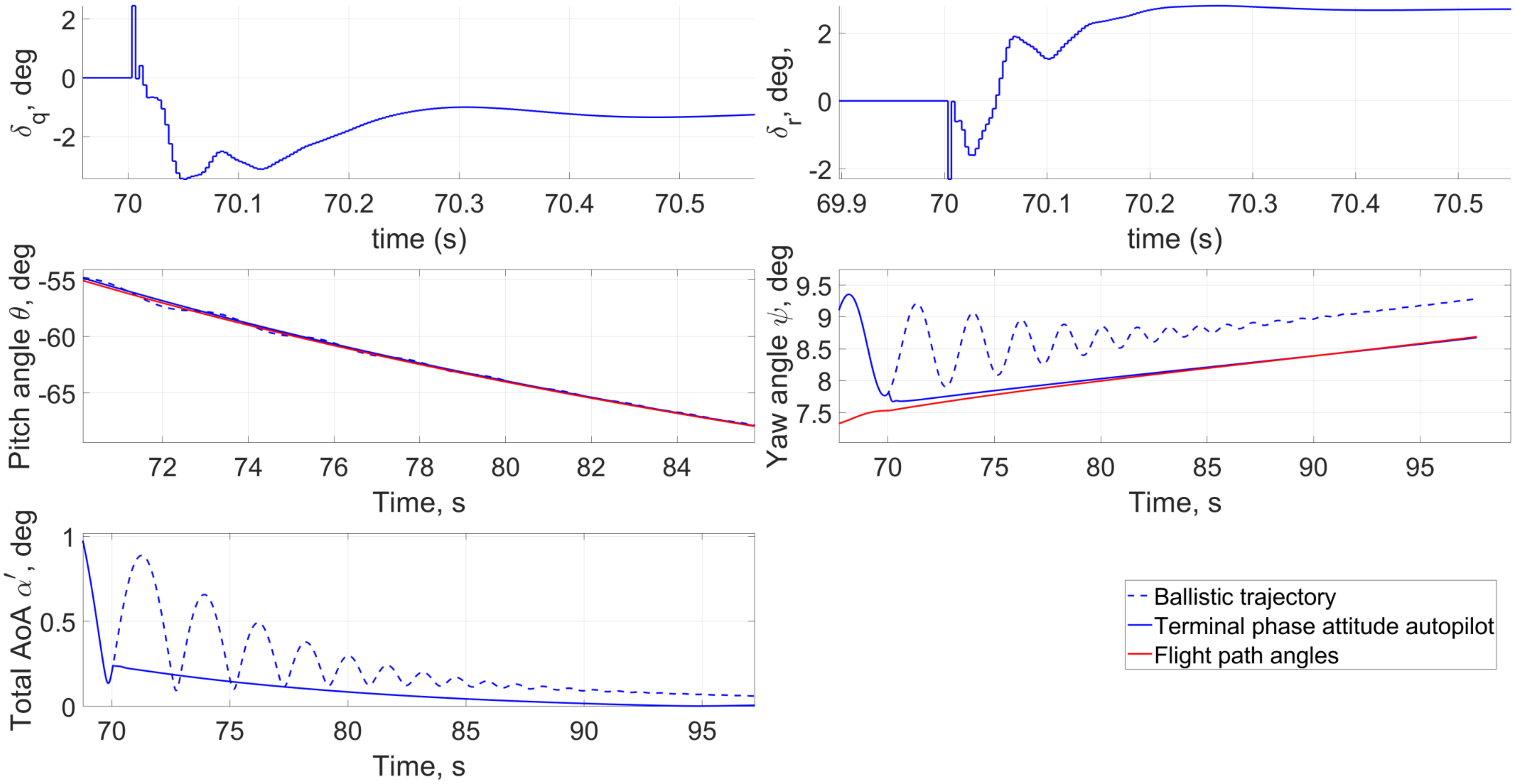


Fig.18: *Terminal phase attitude autopilot – reduced aerodynamic angle scenario*

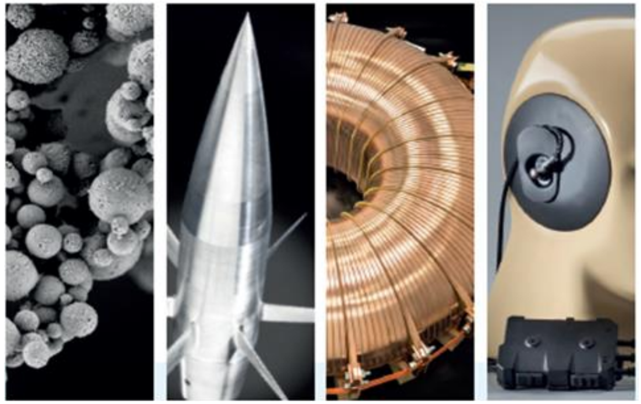
Conclusions & Future work

❑ Conclusion

- A **practical** and **straightforward** nonlinear autopilot design methodology using **discrete time INDI** has been proposed and successfully used on both roll and lateral channel of the projectile dynamics resulting in the design of an unconventional **terminal phase attitude autopilot**.
- Results enlighten the interest of taking into account digital constraints during the design process as it impacts INDI performance.

❑ Future work

- Investigation of solutions to reduce the effect of measurement delays and sensor noise on INDI stability.
- Performance analysis of INDI in presence of parametric (e.g. aerodynamic) uncertainties and wind turbulence.
- INDI augmented structure with adaptive control to reduce impact of uncertainties.



Thank you for your attention.

Appendix 1 : Modified continuous design

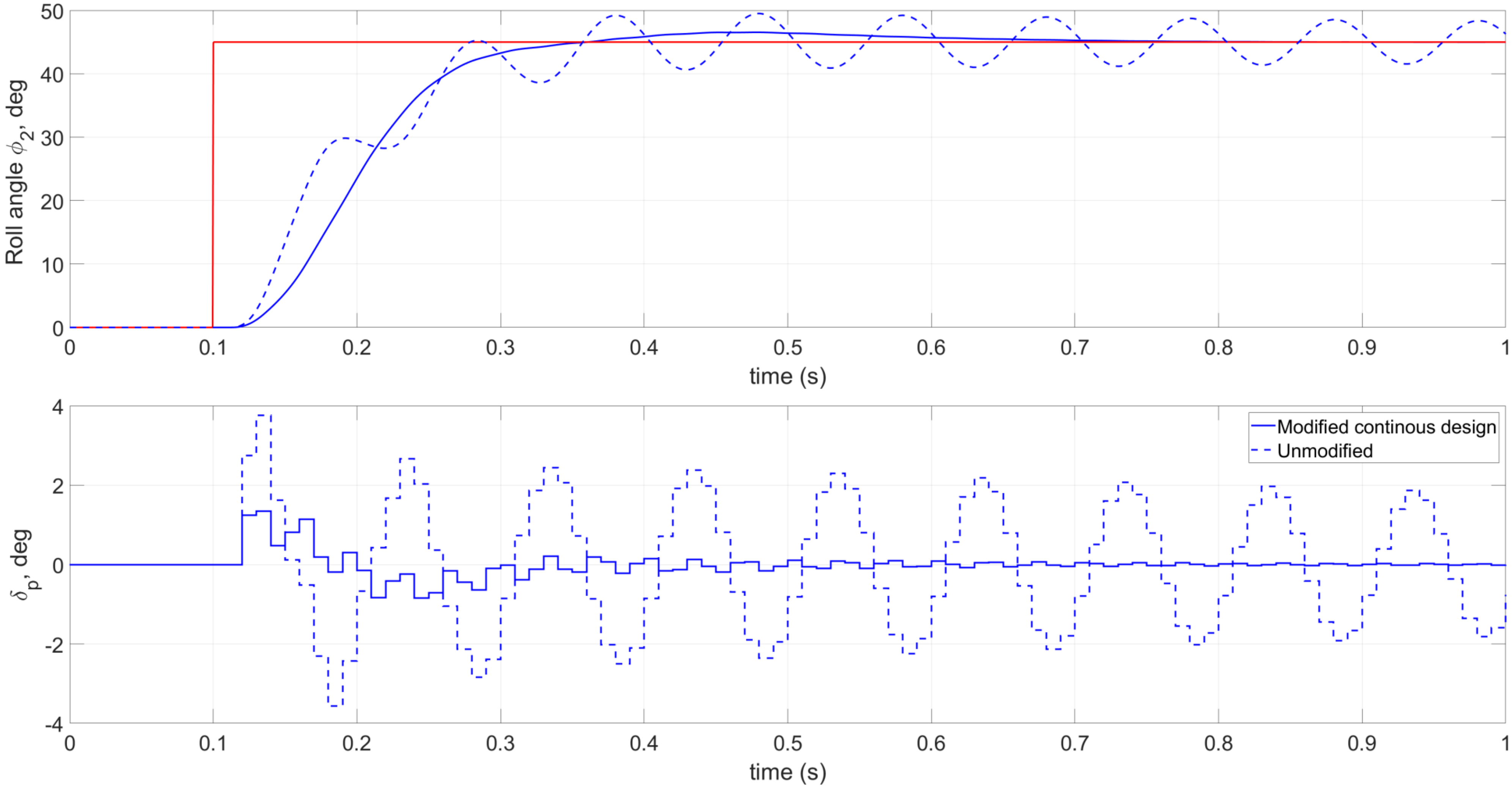


Fig.19: *Response of digital controller using modified and unmodified continous-time design*