SCI-328 Symposium
Flight Testing of Unmanned Aerial Systems (UAS)
Segovia, Spain, 12-13 May 2022

Analysis of the longitudinal stability of a bioinspired morphing UAV

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1.0 INTRODUCTION

2.0 LONGITUDINAL STABILITY ANALYSIS

3.0 FLIGHT CONTROL SYSTEM

4.0 REDESIGN OF THE FLIGHT CONTROL SYSTEM

5.0 CONCLUSIONS

1.0 INTRODUCTION

The National Institute for Aerospace Technology (INTA) is developing Bioinspired Unmanned Aerial Vehicles (UAVs).

Wing-grid model

Winglets at the tip of the wing to simulate the primary feathers of birds.

Morphing model

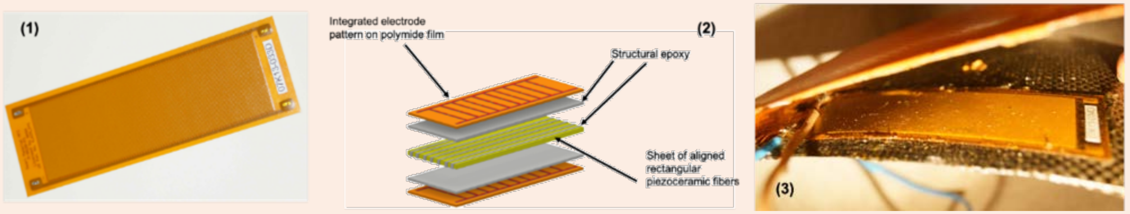
Adaptative wing geometry by using Macro Fiber Composite (MFC) actuators.

1.0 INTRODUCTION

Morphing Configuration.

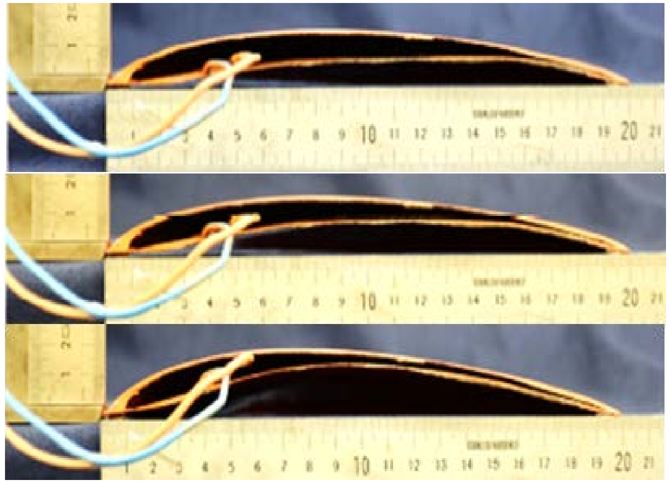
Bioinspired morphing UAV

Piezoelectric actuators (MFC – Macro Fiber Composite) in the inner part of the wing to modify the curvature.



Some aspects of MFC. (1) M-8528-P1 actuator manufactured by Smart Material Corp selected; (2) MFC structure; (3) Detail of MFC installation over inner part of the wing.

- **Morphing concept:** can be defined as the ability of an aircraft to adapt the geometry of its wings to each flight condition by optimizing the aerodynamic performance in each of them.



Airfoil curvature with 500 V. No deformation.

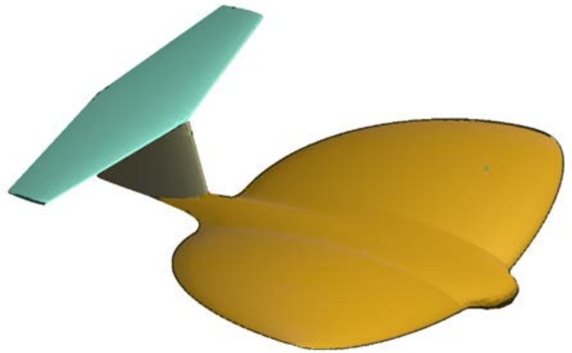
Airfoil curvature with 1000 V.

Airfoil curvature with 1500 V. Maximum deformation.

Increased wing curvature

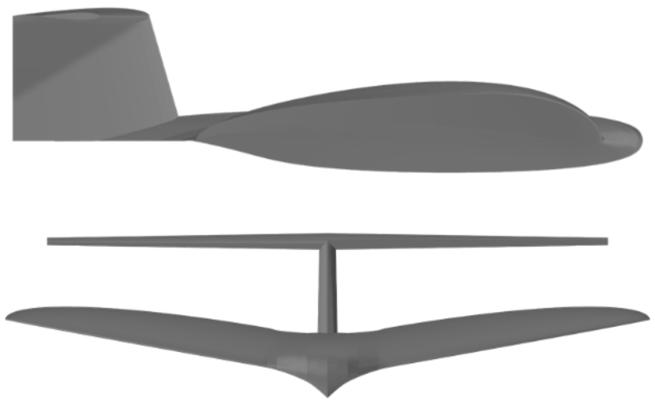
1.0 INTRODUCTION

Bioinspired morphing UAV



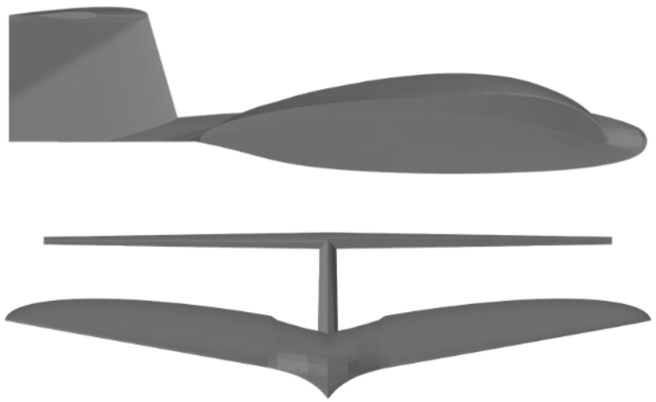
- T-tail
- Zimmerman wing
- Wingspan of 320 mm
- Length of 300 mm

Base configuration



No wing deformation

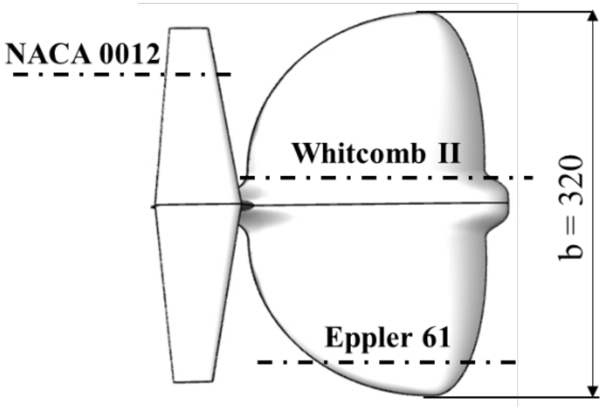
Modified configuration

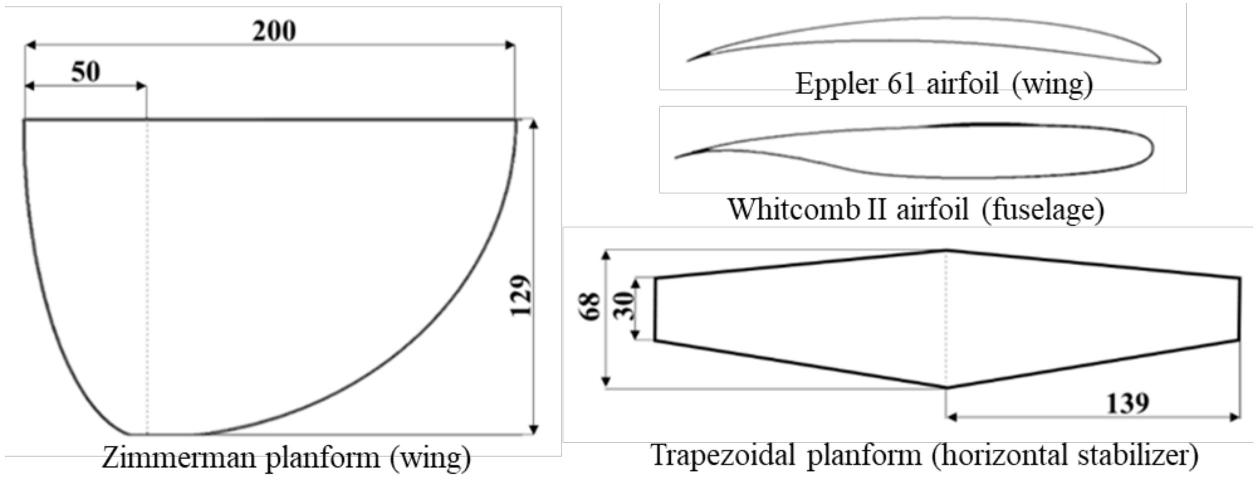


Maximum wing deformation

1.0 INTRODUCTION

Geometry.



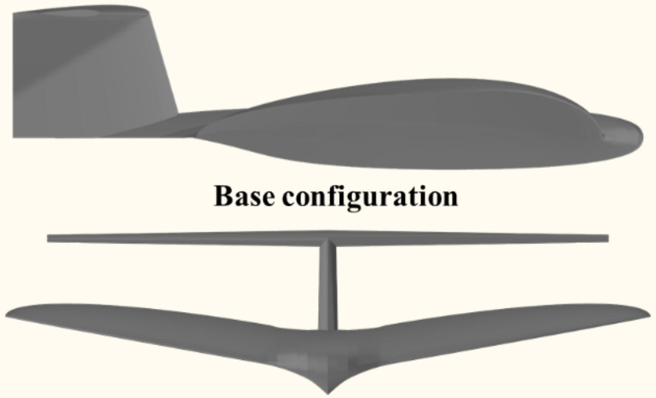


- ❑ Zimmerman wing (Eppler 61).
- ❑ T-tail (NACA 0012).
- ❑ Fuselage (Whitcomb II)

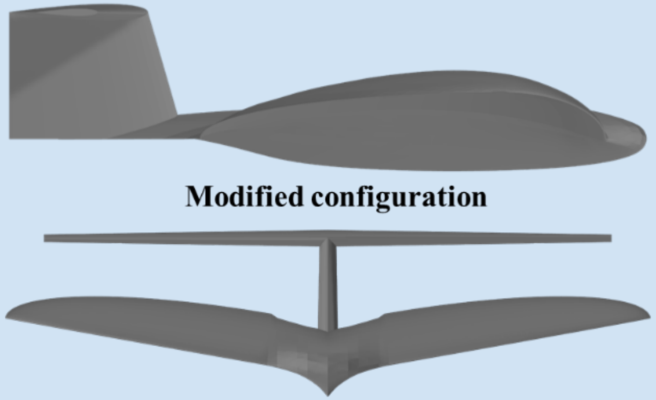
Geometrical Features	Value	Geometrical Features	Value
Reference wing surface, S_{ref}	40.000 mm^2	Mean aerodynamic chord, MAC	141 mm
Fuselage length, l	300 mm	Mean geometry chord, MGC	127 mm
Fuselage width, d	60 mm	Taper ratio, λ	0.124
Wingspan, b	320 mm	Aspect ratio, AR	2.500
Wing tip chord, c_t	25 mm	Dihedral angle, D_h	10°

1.0 INTRODUCTION

- **<u>Objective:</u>** Redesign the **Flight Control System** for the modified configuration to **improve the dynamic response** of the UAV.



Flight Control System based on a Stability Augmentation System (SAS) together with a PID-based pitch autopilot.



<u>Design a Flight Control System</u>

same PID coefficients??

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2.0 LONGITUDINAL STABILITY ANALYSIS

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4.0 REDESIGN OF THE FLIGHT CONTROL SYSTEM

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2.0 LONGITUDINAL STABILITY ANALYSIS

Longitudinal stability analysis of the base and modified UAV configuration.

$\hat{u}$: non-dimensional velocity.
α: angle of attack.
q: pitch rate.
θ: pitch angle.

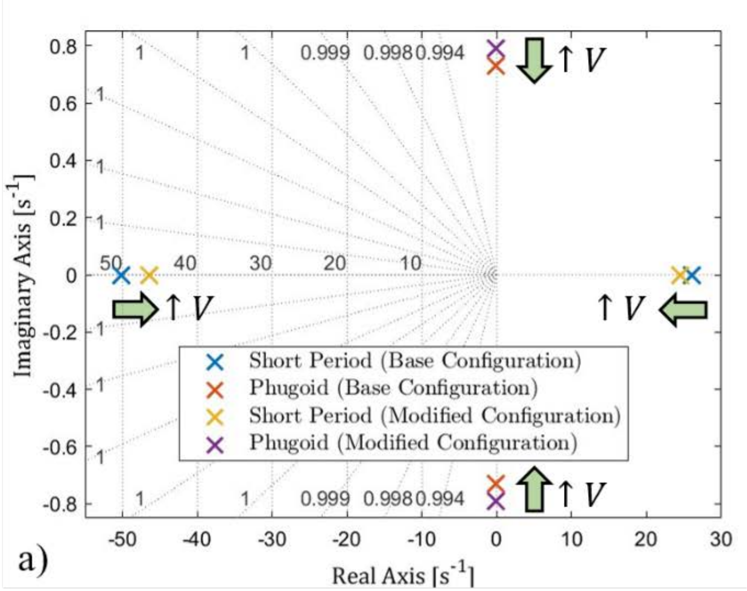
$$c_{m_\alpha} = \frac{\partial c_m}{\partial \alpha} = c_{L_\alpha}(\hat{x}_{cg} - \hat{x}_{ac})$$

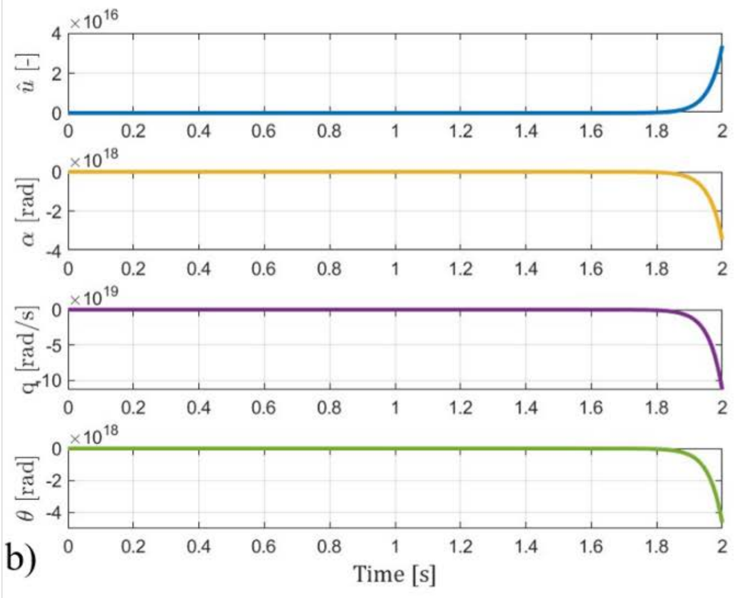
$c_{m_\alpha} < 0$: Statically stable
$c_{m_\alpha} > 0$: Statically unstable

XFLR5 software

$$c_{m_\alpha}^{modified} = 0.67567 \text{ rad}^{-1} > 0$$

$$c_{m_\alpha}^{base} = 0.65744 \text{ rad}^{-1} > 0$$





Statically unstable both UAV configurations !

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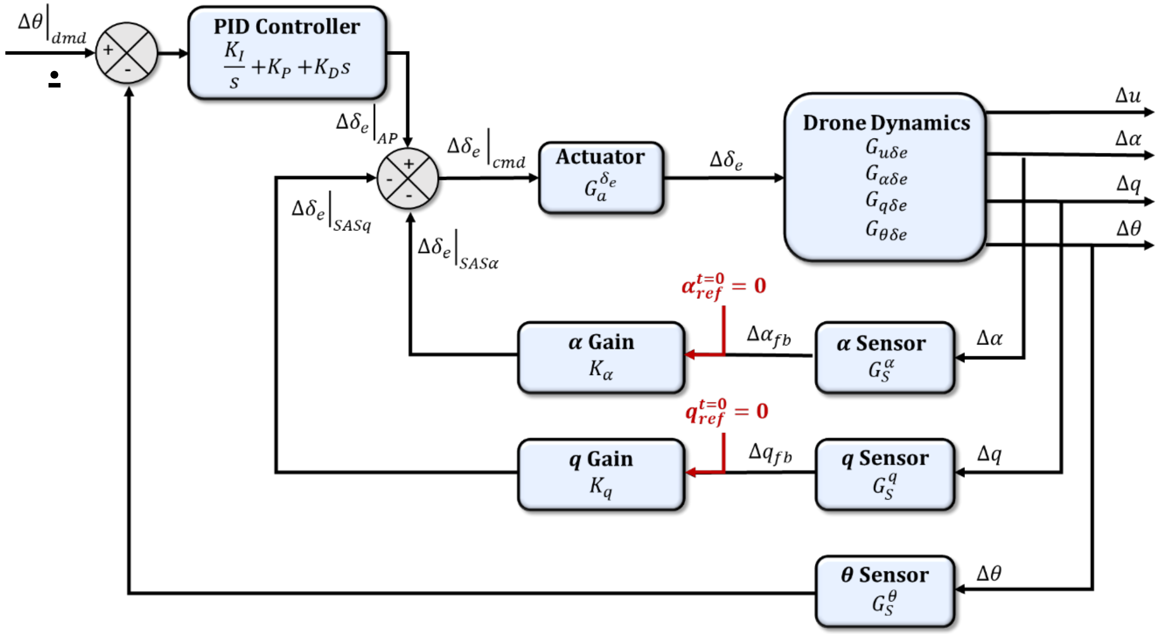
3.0 FLIGHT CONTROL SYSTEM

Flight control system for the base configuration.

Diagram of the PID-based pitch angle autopilot with an integrated stability augmentation system.



The **sensors** and **actuator** involved in the flight control system were modeled as second order transfer functions:

$$G_a^{\delta e} = \frac{w_a^2}{s^2 + 2\xi_a w_a s + 2w_a^2}$$

Characteristic frequency of the actuator, $w_a = 1/\tau_a$
Response delay, $\tau_a = 0.01$ s
Damping coefficient, $\xi_a = 0.8$

$$G_s = \frac{s^2 - 2w_s s + 2w_s^2}{s^2 + 2w_s s + 2w_s^2}$$

Characteristic frequency of the actuator, $w_s = 2/\tau_s$
Response delay, $\tau_s = 0.005$ s

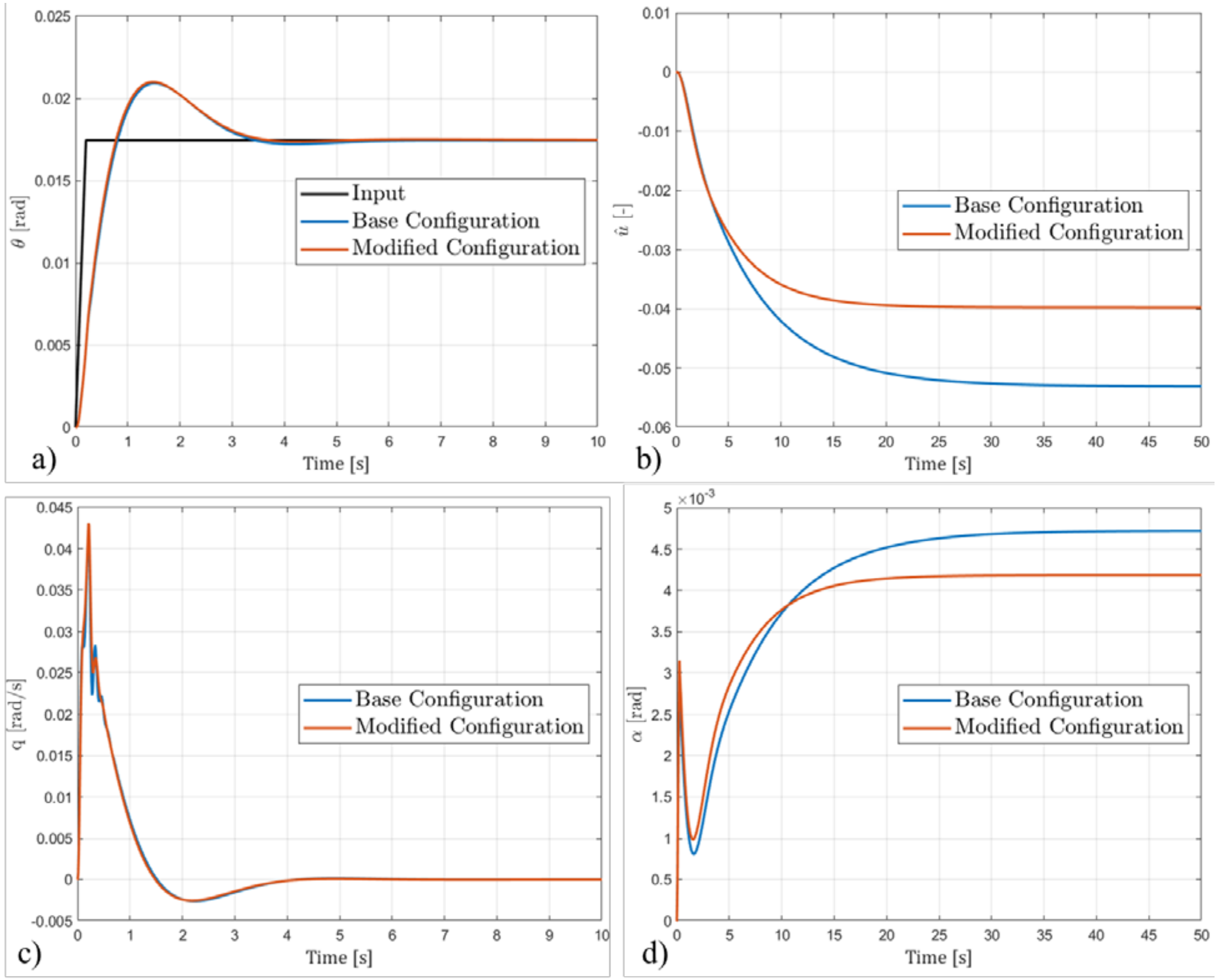
K_α	K_q	K_P	K_I	K_D
−1.375	−0.05	−0.15	−0.18	−0.004

Statically stable the base configuration !

3.0 FLIGHT CONTROL SYSTEM

- **Same gains for both UAV configurations.**
- Perturbation of the elevator deflection:
  1. The non-dimensional velocity $\hat{u}$ and angle of attack α time responses differ significantly. Due to the geometrical change.
  2. The pitch angle θ and pitch rate q time responses remains the same in both configurations.

Redesign the Flight Control System Gains for the modified UAV configuration.



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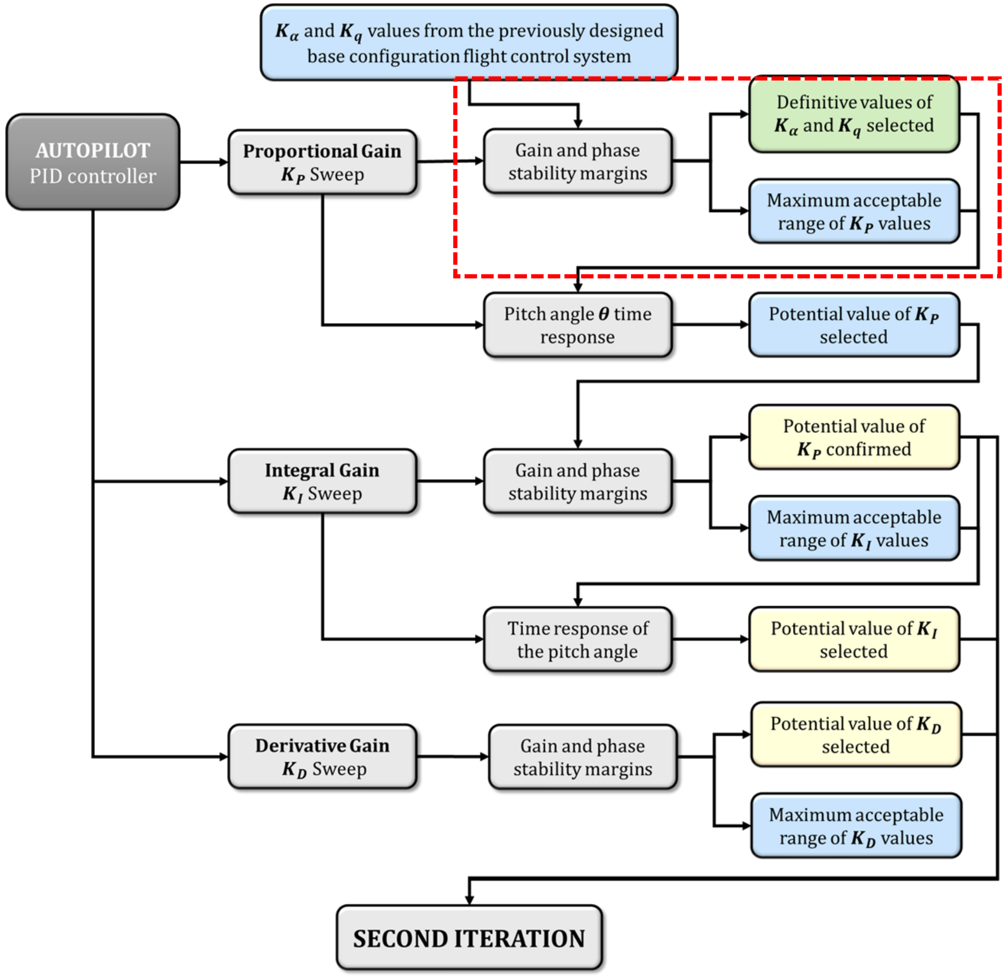
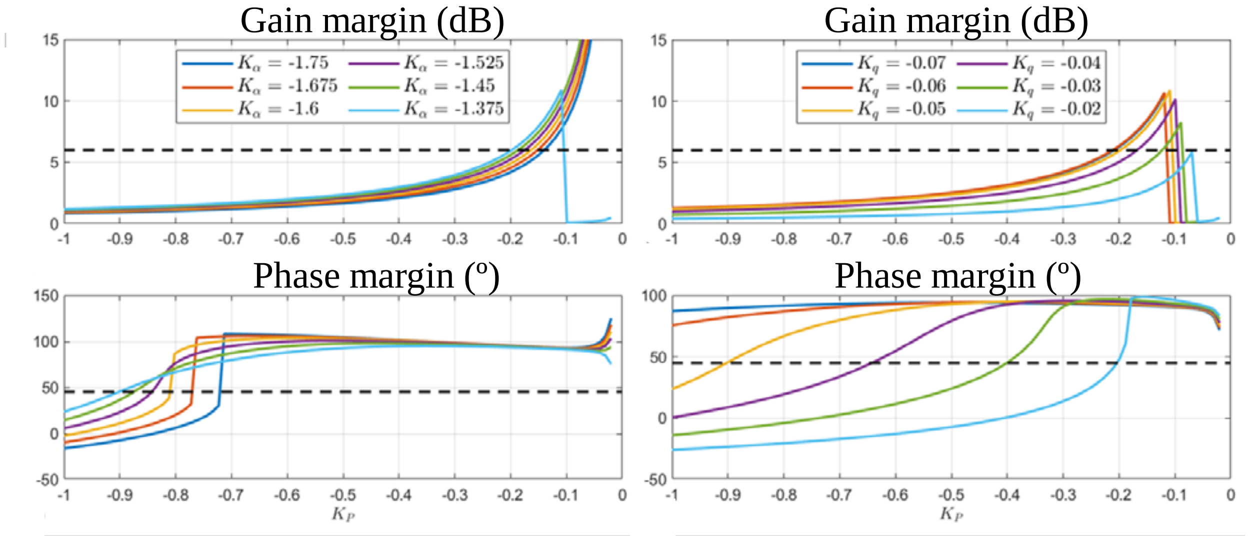
4.0 REDESIGN OF THE FLIGHT CONTROL SYSTEM

Criteria: $GM_{\min} = 6$ dB and $PM_{\min} = 45°$.



Selection of K_α and K_q gains



Gains obtained for the base UAV configuration

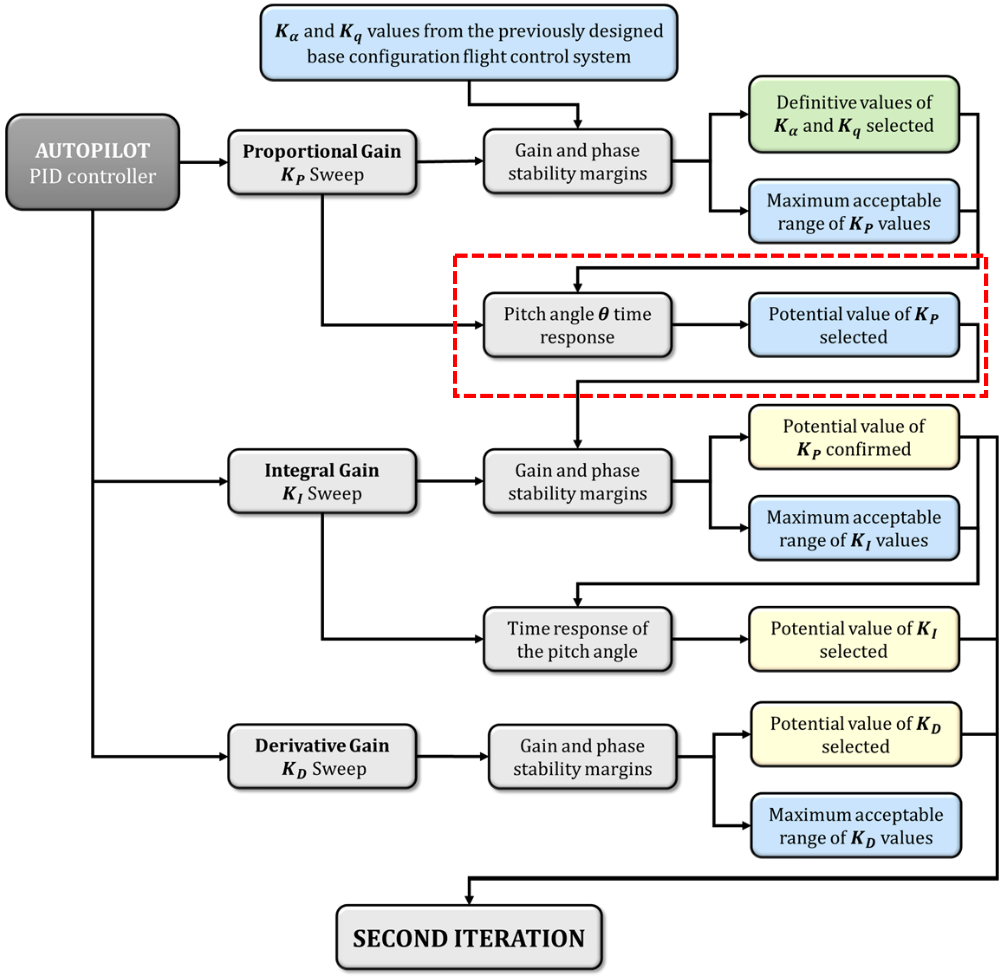
K_α	K_q	K_P	K_I	K_D
-1.375	-0.05	-0.15	-0.18	-0.004

Gains obtained for the modified UAV configuration

$$K_\alpha = -1.375\,;\; K_q = -0.06$$

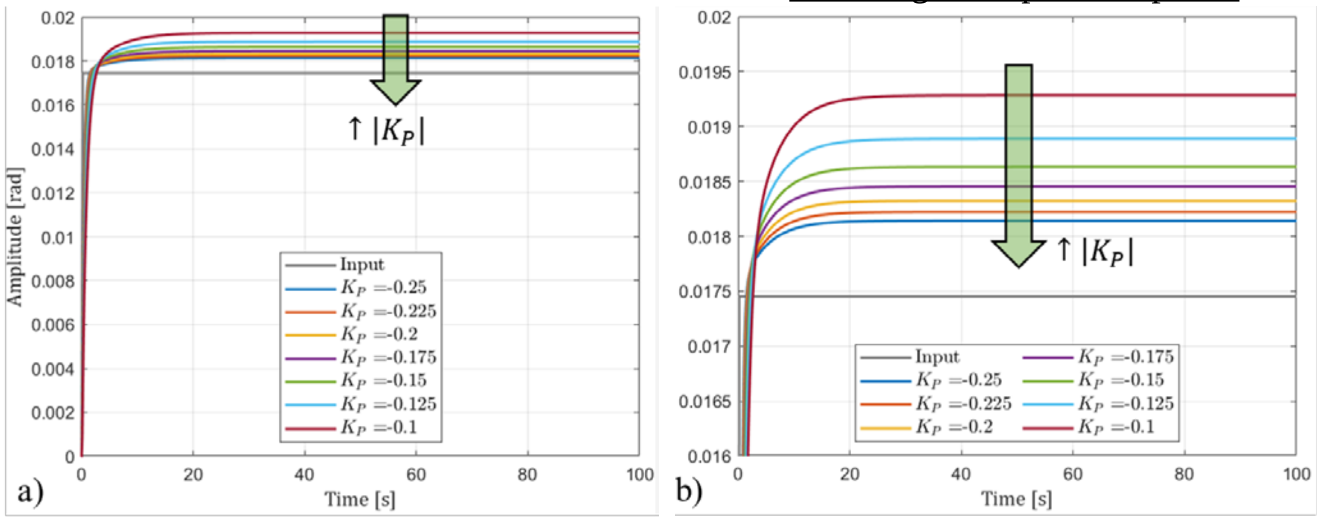
4.0 REDESIGN OF THE FLIGHT CONTROL SYSTEM

$$K_\alpha = -1.375\,;\; K_q = -0.06$$



Selection of K_P

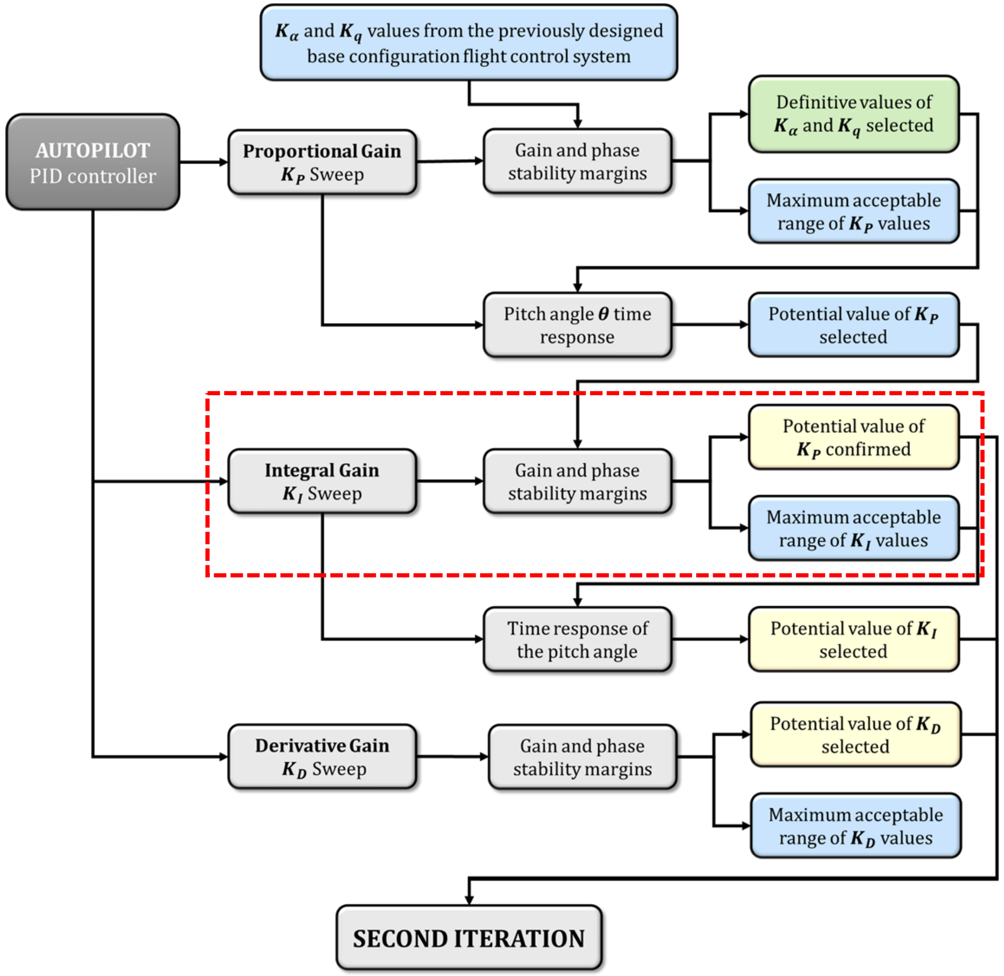
Pitch angle temporal response



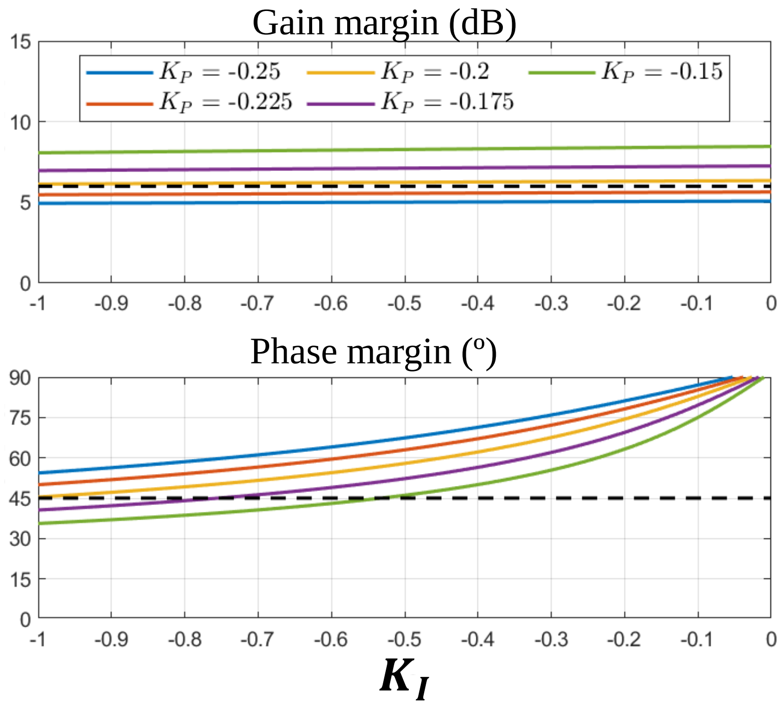
- $\Uparrow |K_P|$ would be desirable because:
  - The stationary error is reduced.
  - The rise time is slighty reduced.
  - The system response is improved.

4.0 REDESIGN OF THE FLIGHT CONTROL SYSTEM

$K_\alpha = -1.375\ ;\ K_q = -0.06$



Selection of K_p



- Gain margin remains constant for K_p.
- An increase in $|K_P|$ benefits the phase margin, but negatively affects the gain margin.

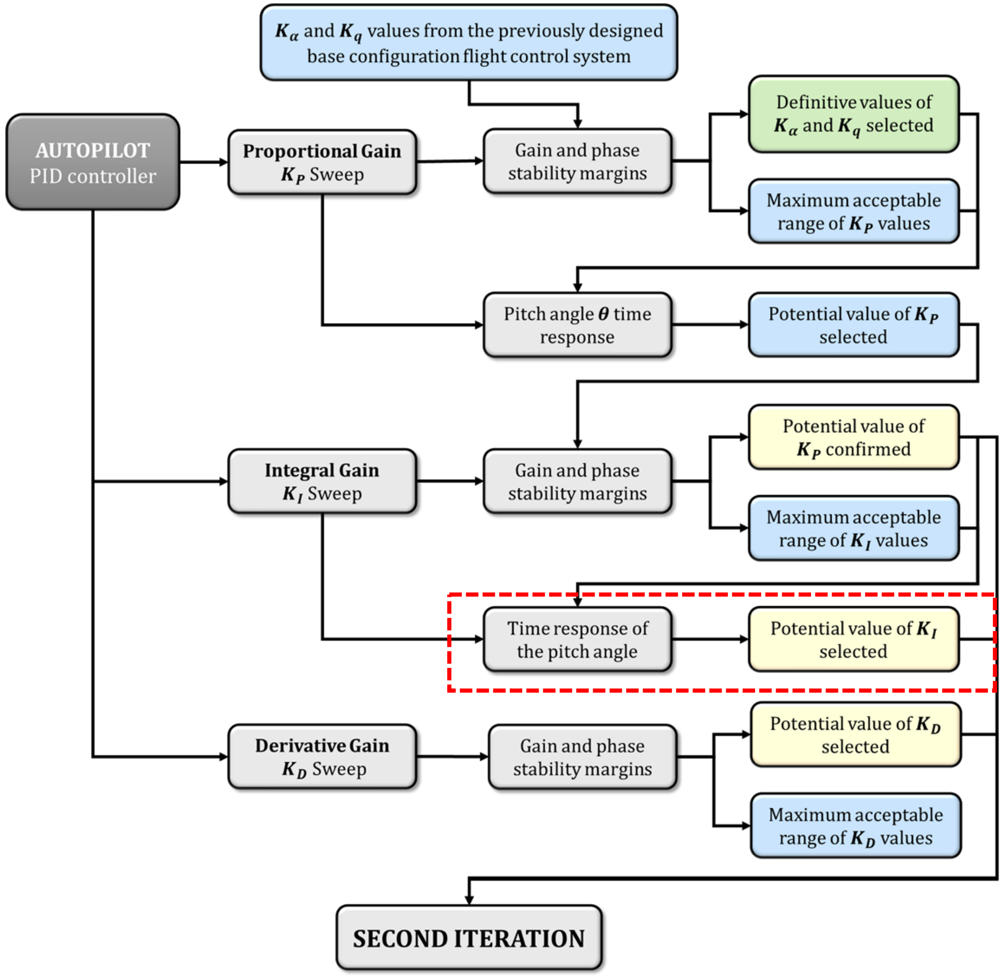
⇩

$K_p = -0.2$

- Any value of K_I could be chosen between -1 and 0.

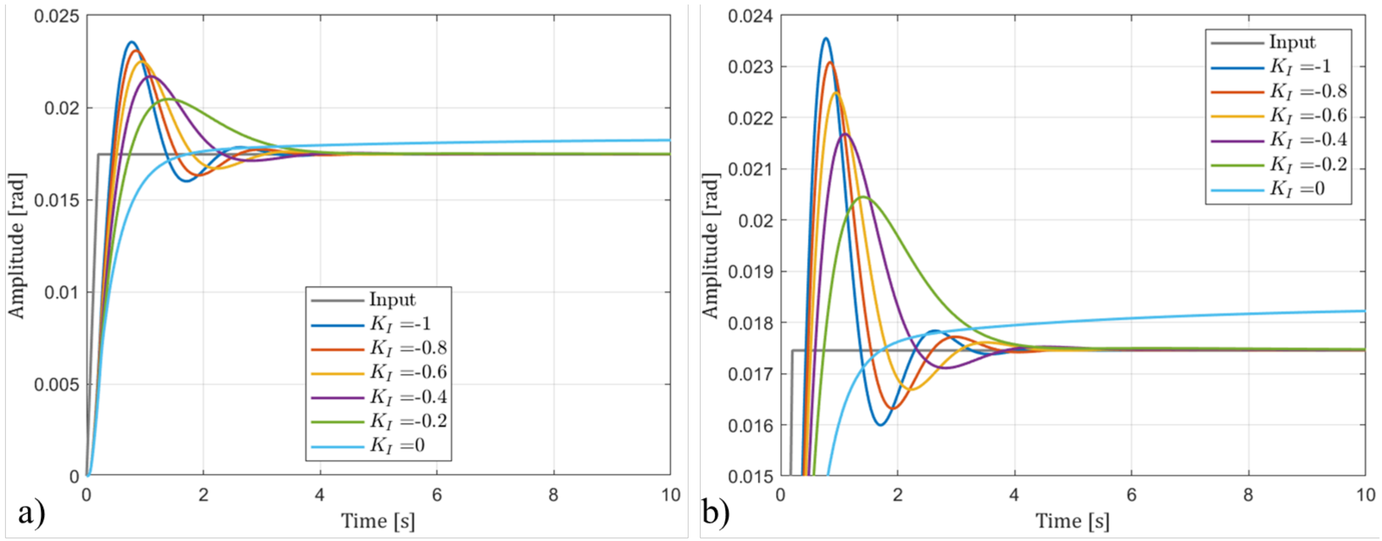
4.0 REDESIGN OF THE FLIGHT CONTROL SYSTEM

$K_\alpha = -1.375; K_q = -0.06; K_p = -0.2$



Selection of K_I

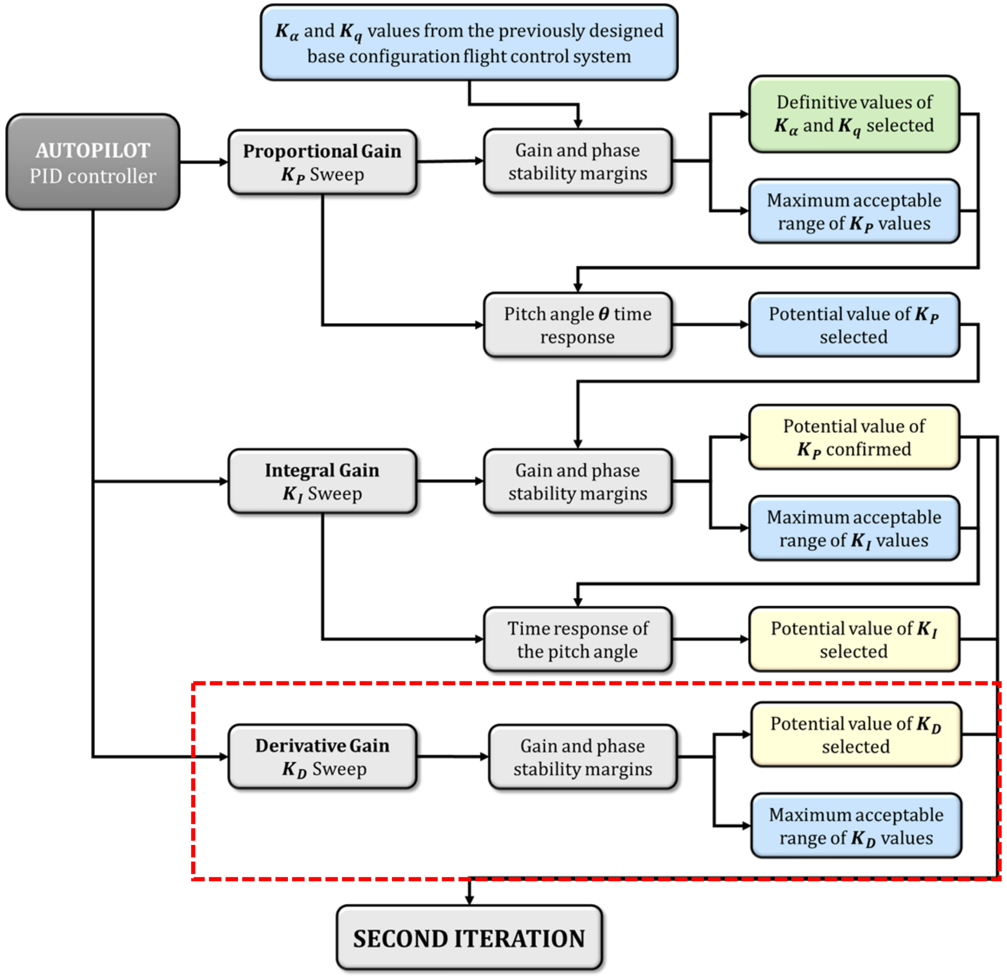
Pitch angle temporal response



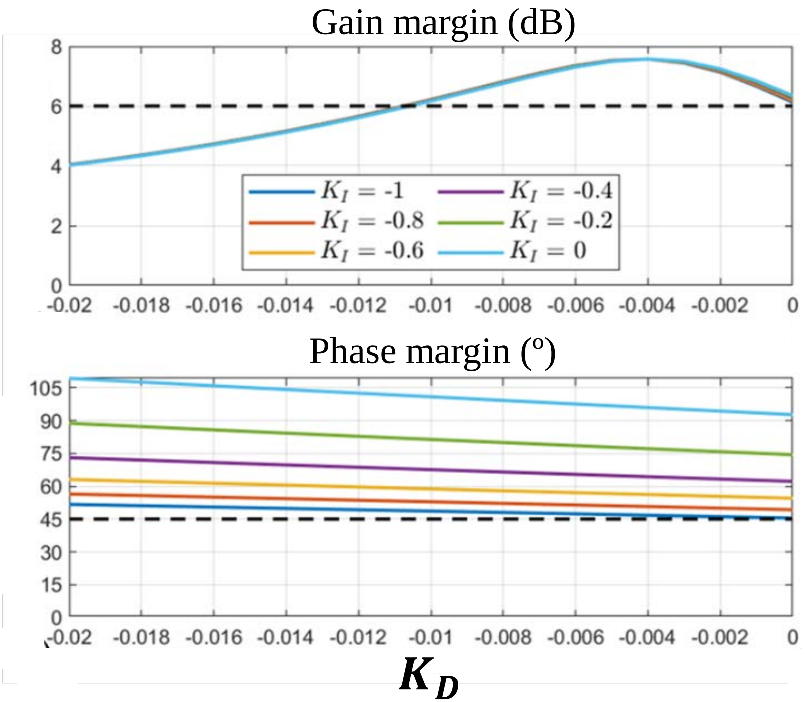
- $|K_I|$:
  - the settling time is reduced.
  - the response becomes under-dampened.
  - the overshoot significantly increases.

$K_I \approx -0.5$

4.0 REDESIGN OF THE FLIGHT CONTROL SYSTEM



Selection of K_I



Very small values of K_D (-0.01 to 0):

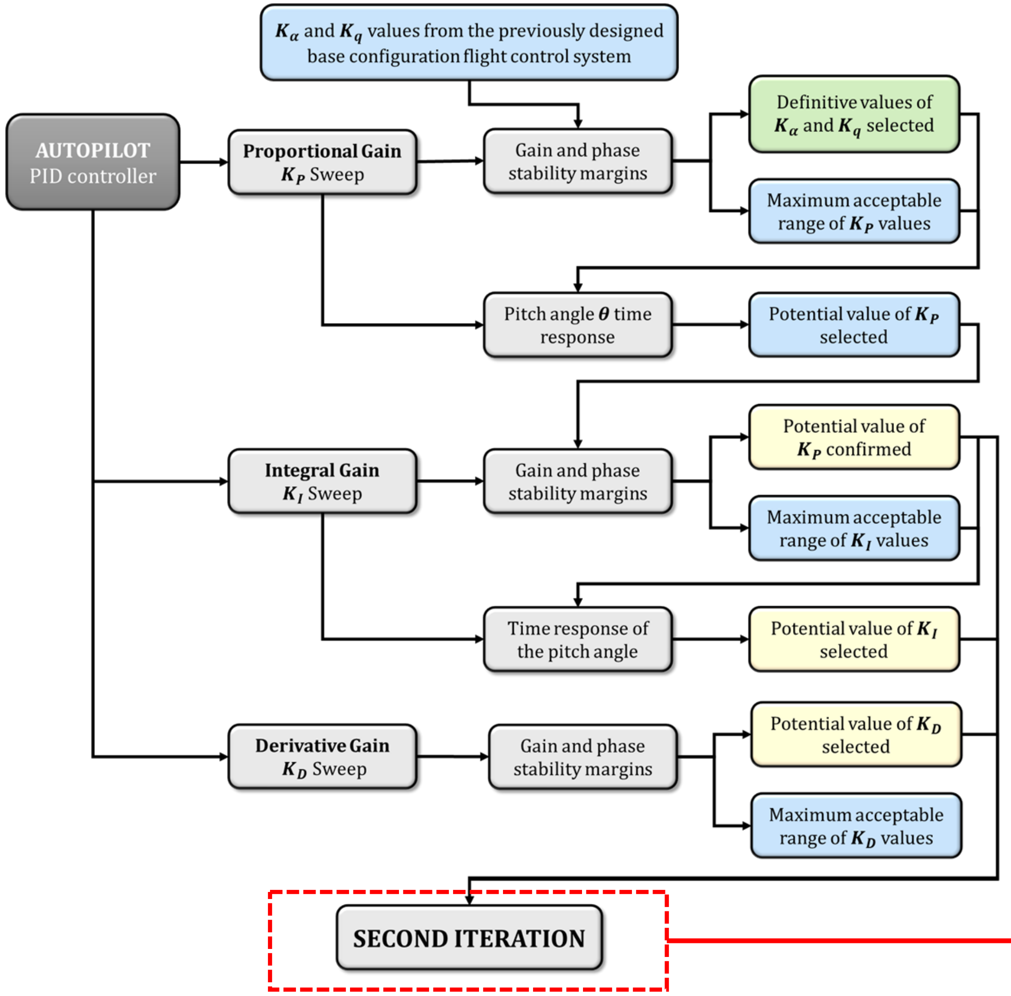
Any value of K_I meets the margin and phase margins.

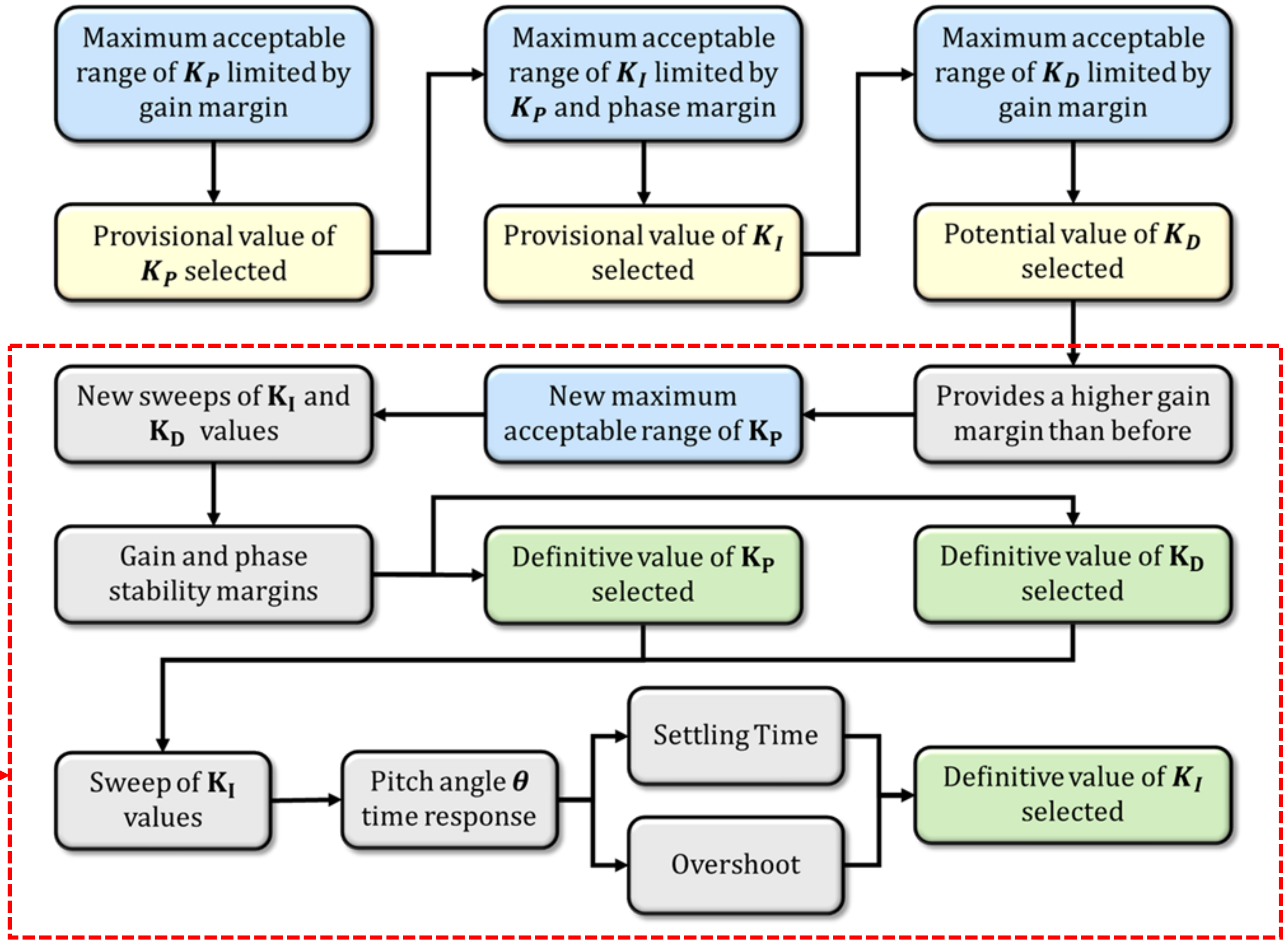
$K_I \approx -0.5$ ✔

- Gain margin goes from about **6 dB to almost 8 dB** ($K_D \approx -0.004$)

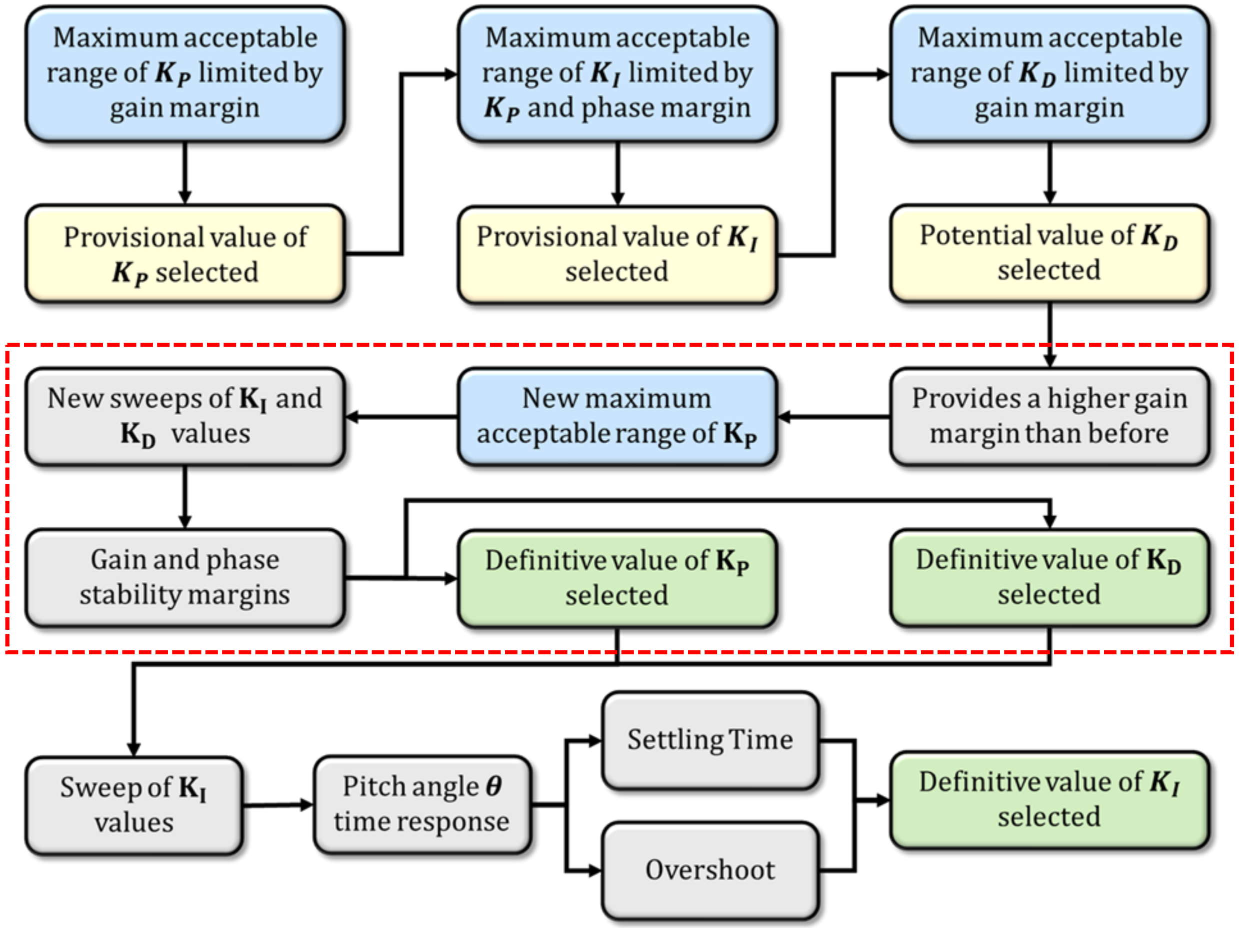
→ K_p can be increased

4.0 REDESIGN OF THE FLIGHT CONTROL SYSTEM

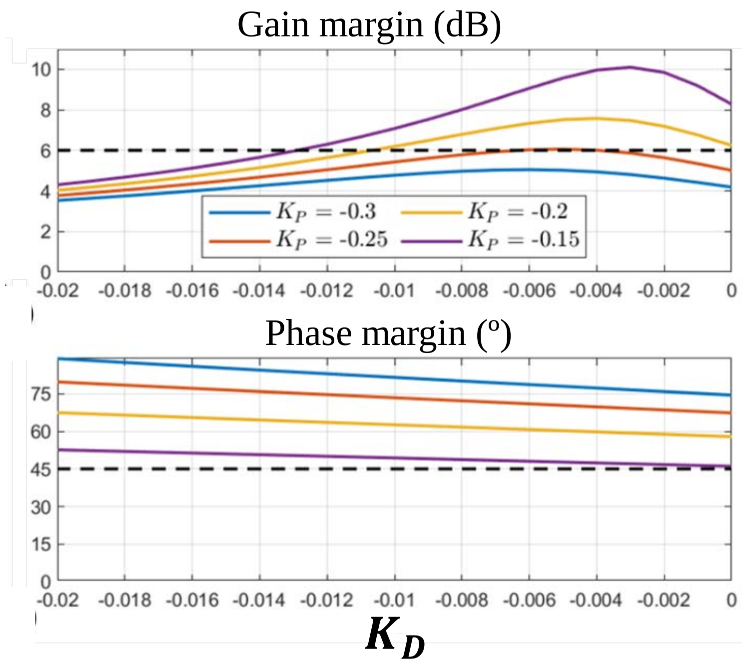




4.0 REDESIGN OF THE FLIGHT CONTROL SYSTEM



Selection of K_p, K_D, K_I



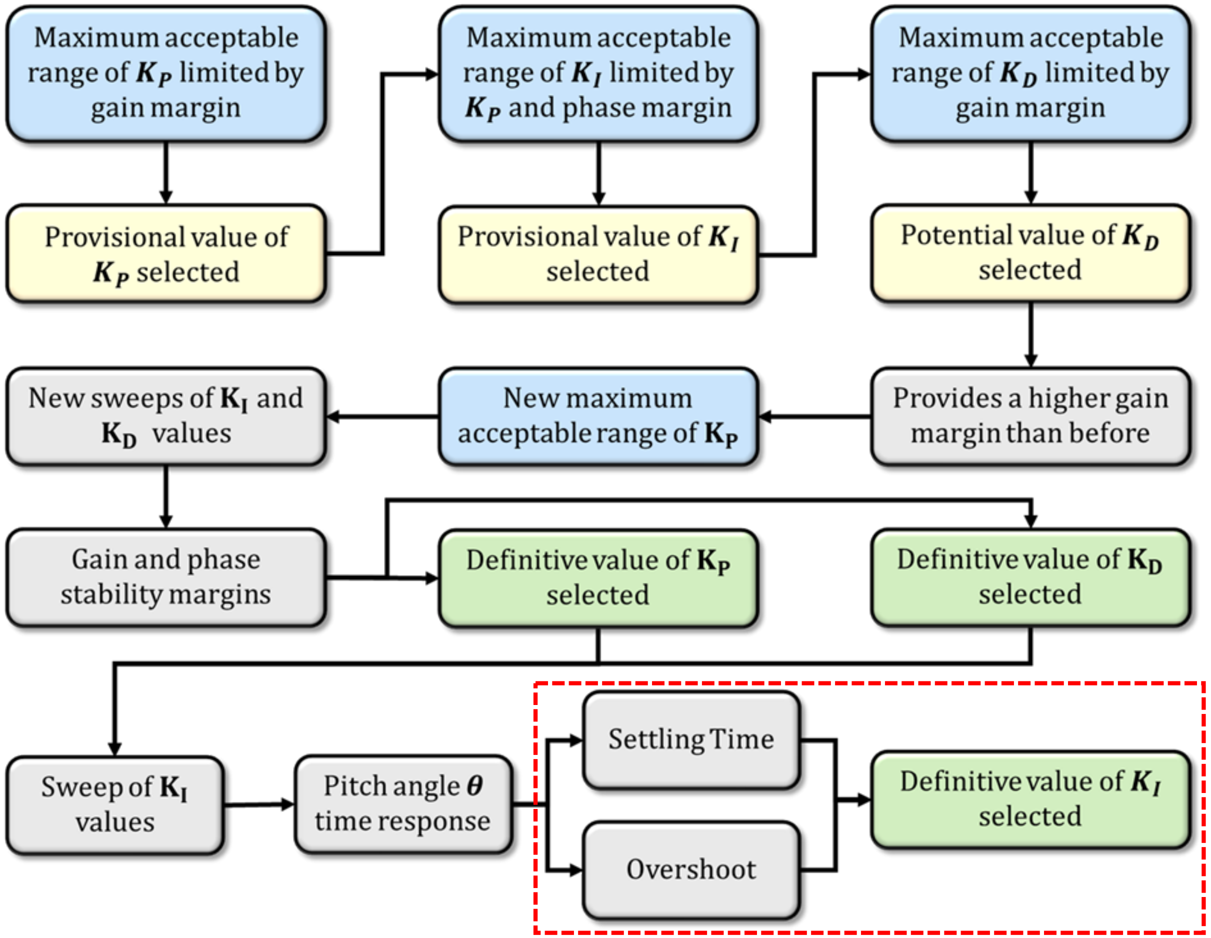
$K_I = -1$

Final gain values

$K_p = -0.25$

$K_D = -0.005$

4.0 REDESIGN OF THE FLIGHT CONTROL SYSTEM

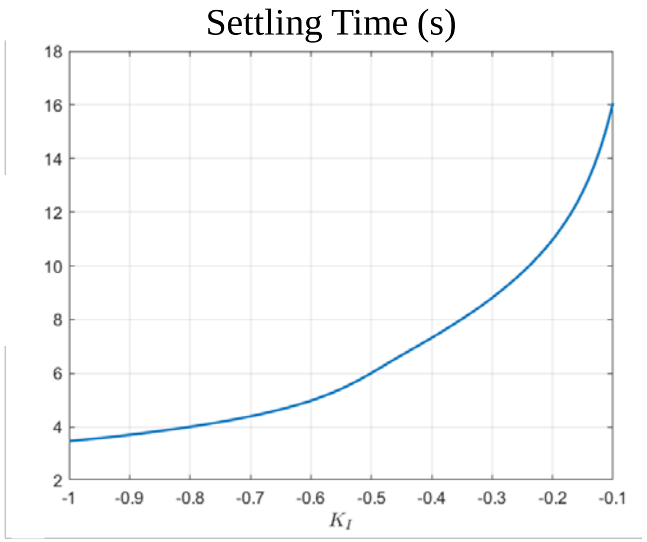


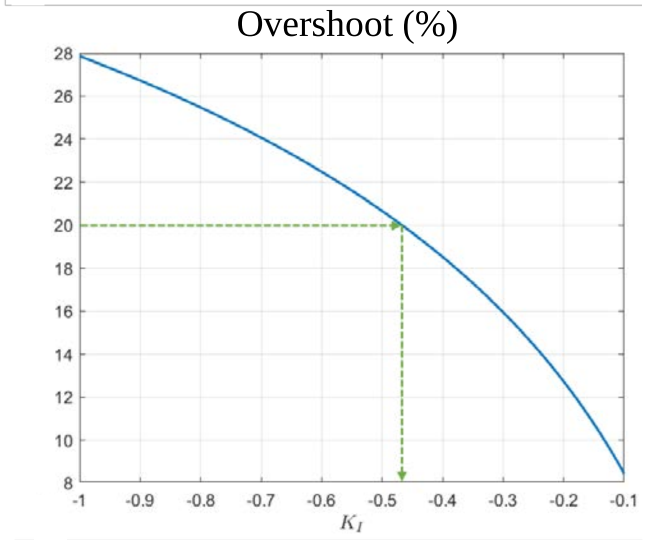
According to Cook in reference "Cook, M., Flight dynamic principles A Linear Systems Approach to aircraft stability and control, Amsterdam etc: Elsevier, 2007."

an overshoot lower than 20% of the stationary value is mandatory for a control system to be considered as adequate.

Final gain value

$$K_I = -0.46$$



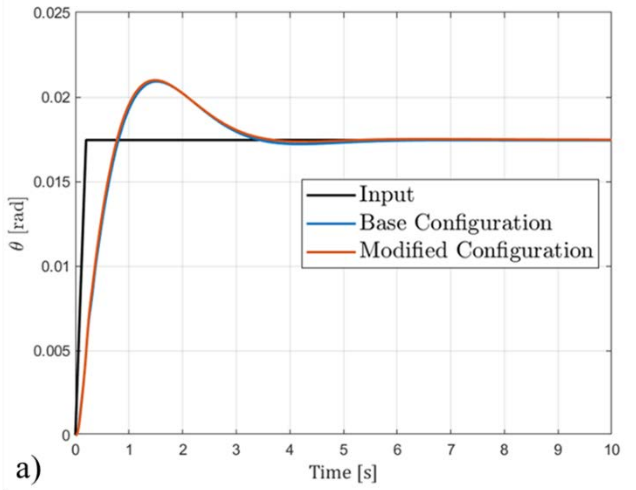


4.0 REDESIGN OF THE FLIGHT CONTROL SYSTEM

Final gains of the redesigned flight control system

	K_α	K_q	K_P	K_I	K_D
Base Configuration	−1.375	−0.05	−0.15	−0.18	−0.004
Modified Configuration	−1.375	−0.06	−0.25	−0.46	−0.005

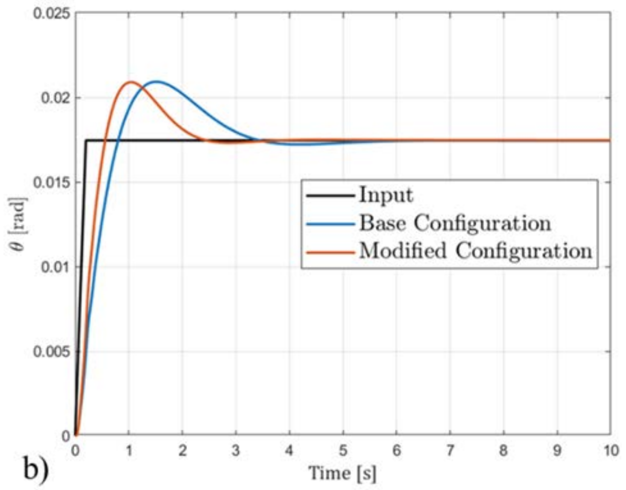
Pitch angle time response



	K_α	K_q	K_P	K_I	K_D
Base Configuration	−1.375	−0.05	−0.15	−0.18	−0.004
Modified Configuration	−1.375	−0.05	−0.15	−0.18	−0.004

- Temporal response is faster with the modified configuration.
- Lower settling time and rise time.
- Dynamic response of the vehicle is improved.

Pitch angle time response



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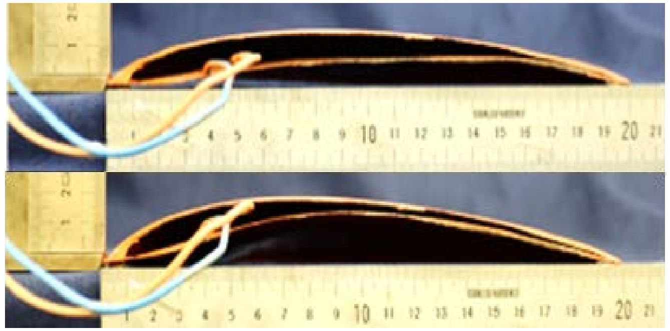
5.0 CONCLUSIONS

- The flight control system of the morphing base configuration has been redesigned for its modified configuration, obtaining **an increased static stability and improved dynamic response.**

- A strict minimum gain and phase margin requirements of 6 dB and 45° have been considered to conduct the redesign of the flight control system, together with a requirement of a maximum overshoot allowed of 20% of the stationary value.

- It has been demonstrated with the redesign that the slight stability improvement of the modified configuration can indeed lead to significant enhancements of the pitch angle dynamic time response if the autopilot gains are optimized.

5.0 CONCLUSIONS

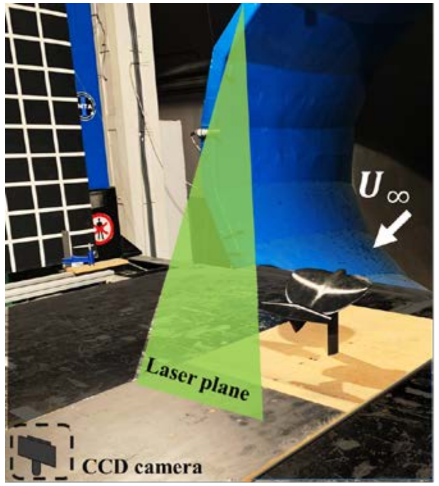


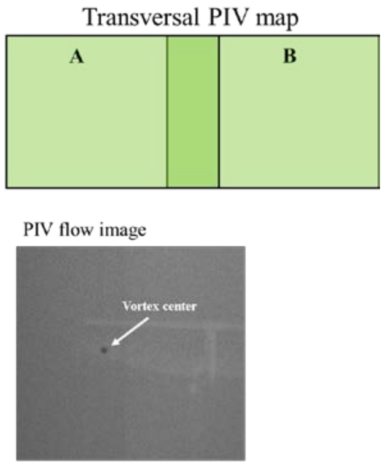
Next steps:

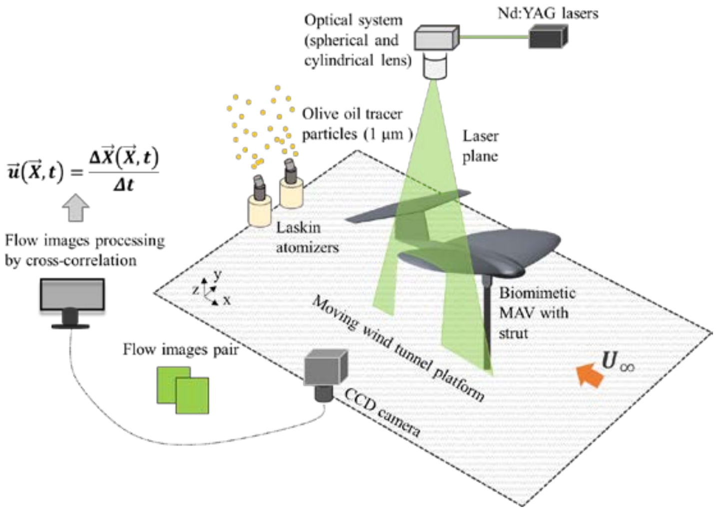
☑ **1st phase:** Design of the morphing UAV.

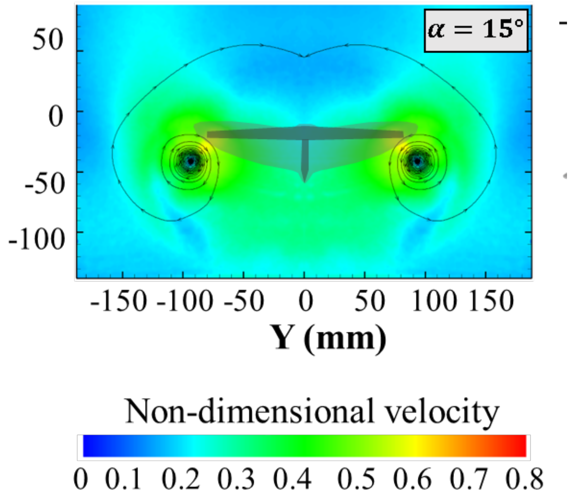
☑ **2nd phase:** Ground testing – base and modified configurations.

☑ **3rd phase:** Aerodynamic characterization – wind tunnel testing and CFD simulation.



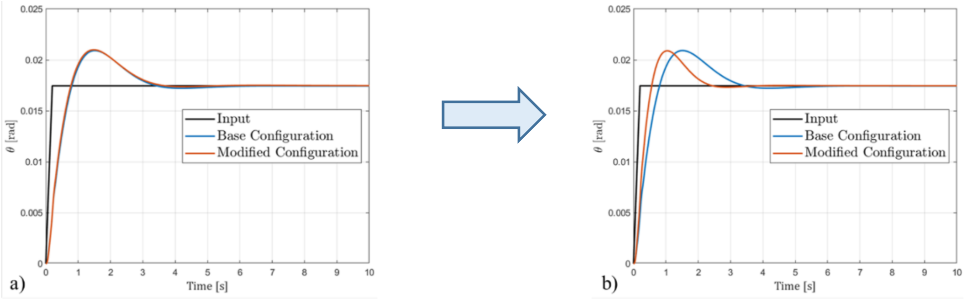






5.0 CONCLUSIONS

- ☑ **4^{th} phase:** Longitudinal Stability of the base and modified UAV configurations.



- ❑ **5^{th} phase:** Set dynamic gains that change with the applied voltage as the curvature changes.
- ❑ **6^{th} phase:** Fabricate real demonstrator with Flight Test Instrumentation.
- ❑ **7^{th} phase:** Flight Testing (pressure sensors, accelerometers and flight data recorders).

THANK YOU FOR YOUR ATTENTION

QUESTIONS?