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SUSTAINABLE AEROSPACE INNOVATION IN A GLOBALISED WORLD

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A study for a MDO process applied to conceptual design of a remotely piloted aircraft

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Overview

Motivation

- Increasing use of remotely piloted aircraft (RPA) for civilian applications:
  - Aerial photography, agricultural, coastguard, power lines inspection, etc.

Austin, 2010

- Availability of equipment (electronics, propulsion)
- Easy manufacturing
- Relatively low cost

RQ-11 Raven

AeroVironment, 2019.

TAI Gözcü

Hurriyet, 2019

AR4 Evolution

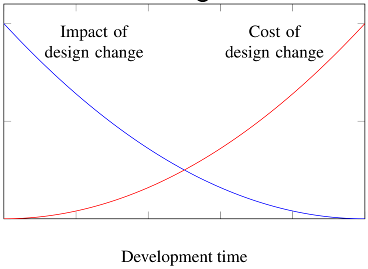
Tekever, 2019.

Conceptual design

Design phases:

- informational - requirements
- conceptual
- preliminary
- detailed
- (manufacturing, operation,)

Costs versus design time



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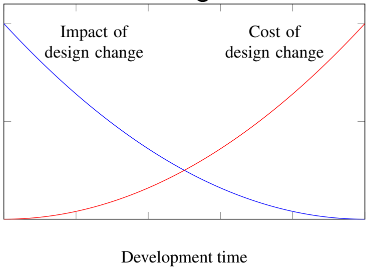


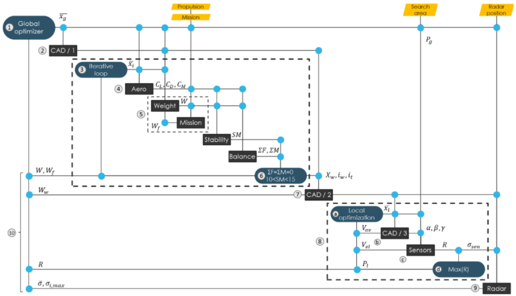
- Design strategy:
  - ◇ Multidisciplinary Design Optimization (MDO) at conceptual level
- Difficulty: establish the architecture

Multidisciplinary design tool

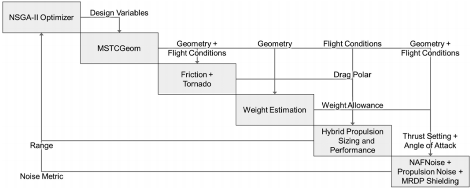
Martins and Lambe (2013) classify the MDO problems into:

- monolithic : a single optimisation problem is solved,
- distributed: the same problem is partitioned into multiple sub problems.

It is necessary to test multiple architectures on a given MDO problem to determine which one is most efficient for each case.



Papageorgiou et al., 2017



Bryson et al., 2016

Multidisciplinary design tool

Sobieszczanski-Sobieski and Haftka (1996) identify three categories of MDO problems:

- those with two or three interactive disciplines, where a single analyst might acquire all necessary knowledge.

  ◇ At analysis level, this can lead to the creation of a new discipline responsible for the interaction between the involved disciplines, as aeroelasticity or thermoelasticity.

- those in which the multidisciplinary optimisation of the entire system is executed at conceptual level by simple analysis tools.

- those that focus in organisation and computational challenges and develops special techniques able of solving them.

Goals

Main goal

Define and implement a framework for conceptual design of a remotely piloted aircraft (RPA)

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Define and implement a framework for conceptual design of a remotely piloted aircraft (RPA)

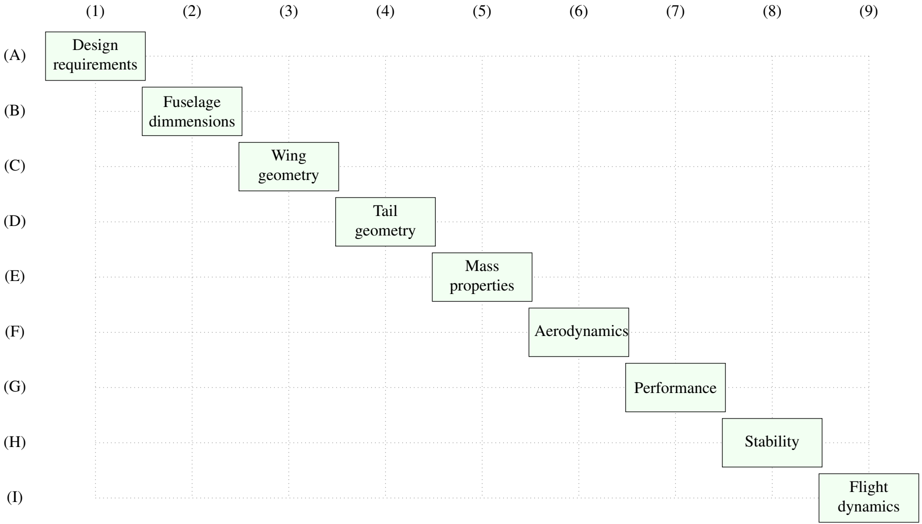
Steps to achieve that:

- Outline clearly the objectives of the conceptual design phase;
- Organise a framework aiming to reach a viable concept that meets the mission requirements;
- Express conceptual design through a block diagram relating the various disciplines addressed in aircraft design;
- Apply an optimization method, defining the project variables, objective function and constraints;

Tool applicability

- Mini UAV category, which is capable of being hand-launched and operating at ranges up to 30 km, according to Austin (2010);
- Aircraft with conventional configuration tractor or pusher with a payload bay with a single tail boom leading to a conventional, cruciform or "T" tail configuration without landing gear and electric propulsion system.

N - diagram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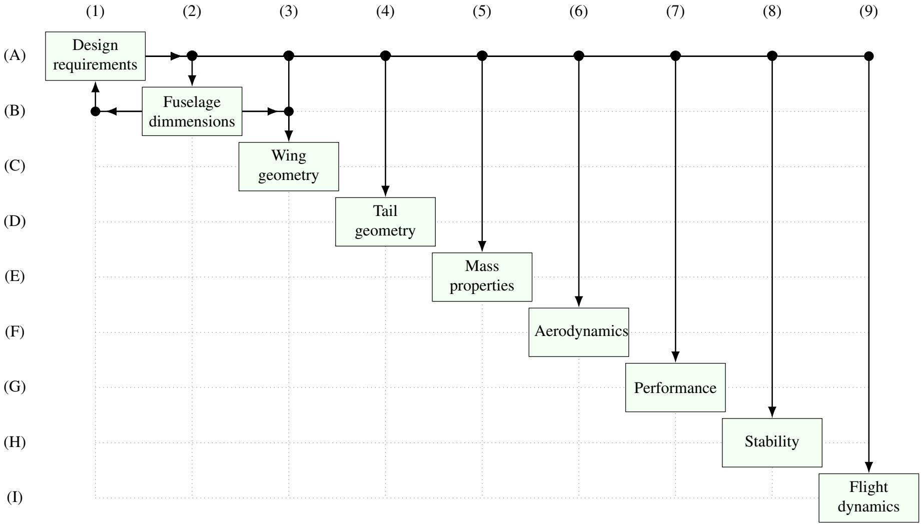
Design requirements
Fuselage dimmensions
Wing geometry
Tail geometry
Mass properties
Aerodynamics
Performance
Stability
Flight dynamics

N - diagram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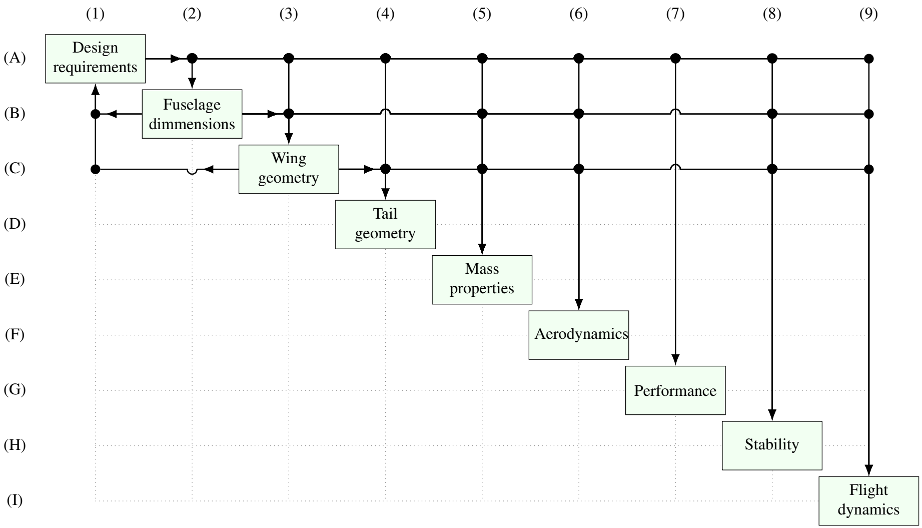
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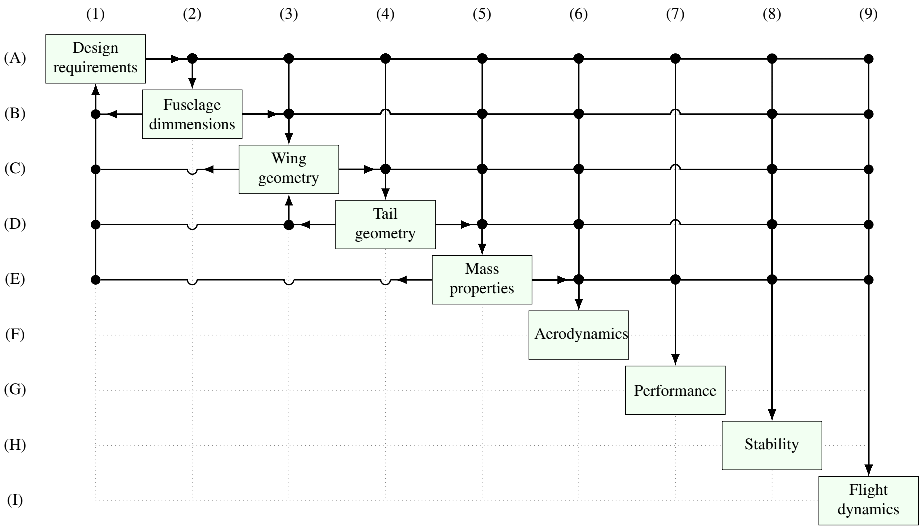
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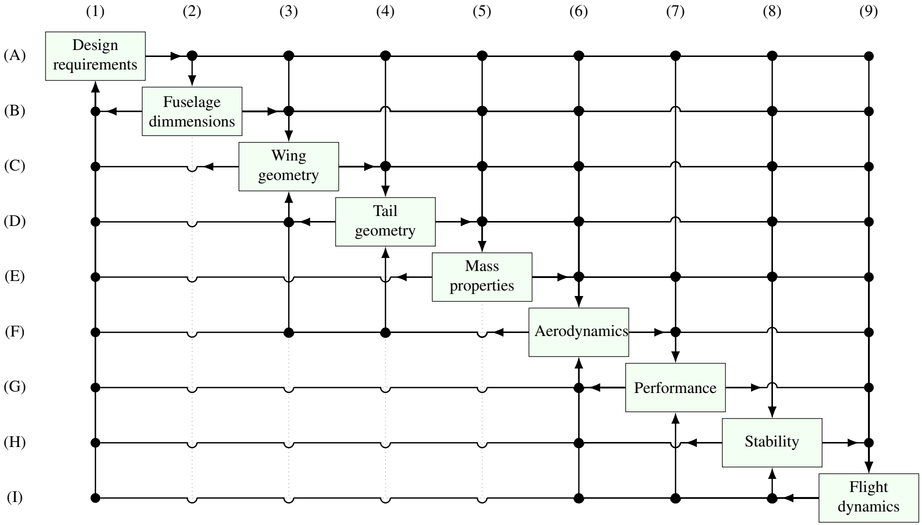
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Remotely piloted aircraft conceptual design

The unmanned aircraft design process differ from the manned ones, once the information source, historic regressions and design coefficients are not available or are not reliable Gundlach, 2012.

- The wing and tail geometry are calculated according to Gudmundsson (2014);
- Weight prediction is based on the volume calculation of each structural component and multiplied by a material density;
- Aerodynamics coefficients are calculated using Roskam Class II methodology Roskam, 1985;
- Performance estimates are found from Traub (2011) formulation;
- Stability derivatives are predicted from empirical data presented in Roskam (1983);
- Flight dynamics are analysed based on Cook (2011) methodology.

Definition of the optimization problem

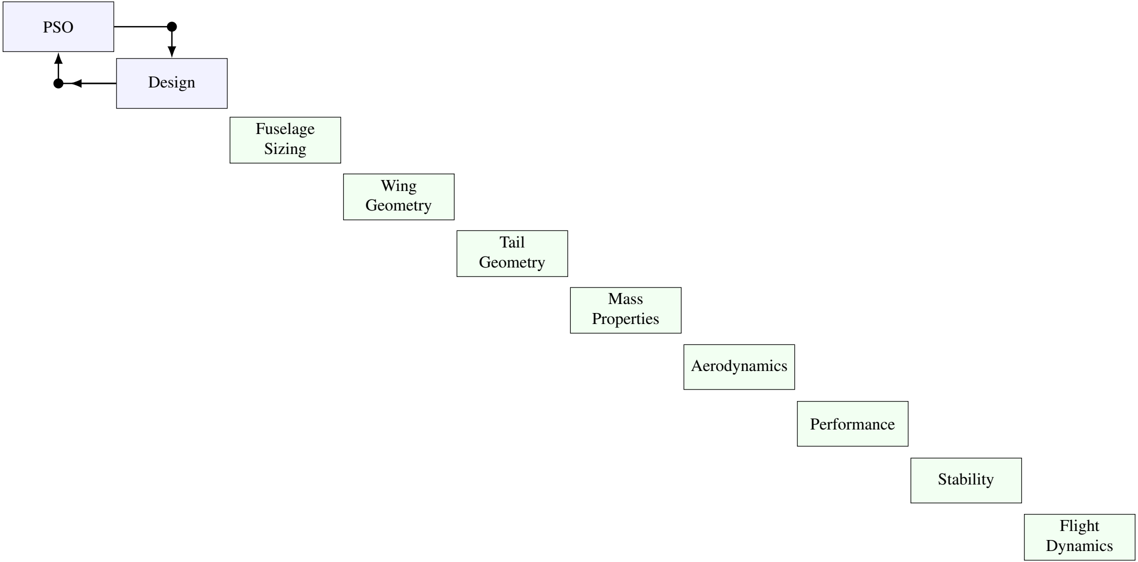
The optimization problem is

$$
\begin{aligned}
\min \quad & f(\mathbf{x},\mathbf{p}) = M_{tot} \\
& \mathbf{x} = [AR \quad S \quad \lambda \quad \Lambda_{LE} \quad \frac{x_{r_w}}{l_{fus}} \quad \lambda_{fus} \quad AR_{HT} \quad AR_{VT} \quad \frac{l_{HT}}{\bar{c}}]^T, \\
& \mathbf{p} = [H \quad V \quad V_{HT} \quad V_{VT} \quad Vol_{fus} \quad C_{Bat} \quad \rho_{Mat} \quad M_{PL} \quad \ldots]^T \\
& x_{i,L.B.} \le x_i \le x_{i,U.B.}, \; i = 1,2,\ldots 9 \\
s.t. \quad & \\
& C_{m_\alpha} < 0, \\
& C_{n_\beta} > 0, \\
& 12.5\% < SM < 17.5\%, \\
& \lambda_{Alp} < 0 \quad e \quad \lambda_{Alg} < 0.
\end{aligned}
$$

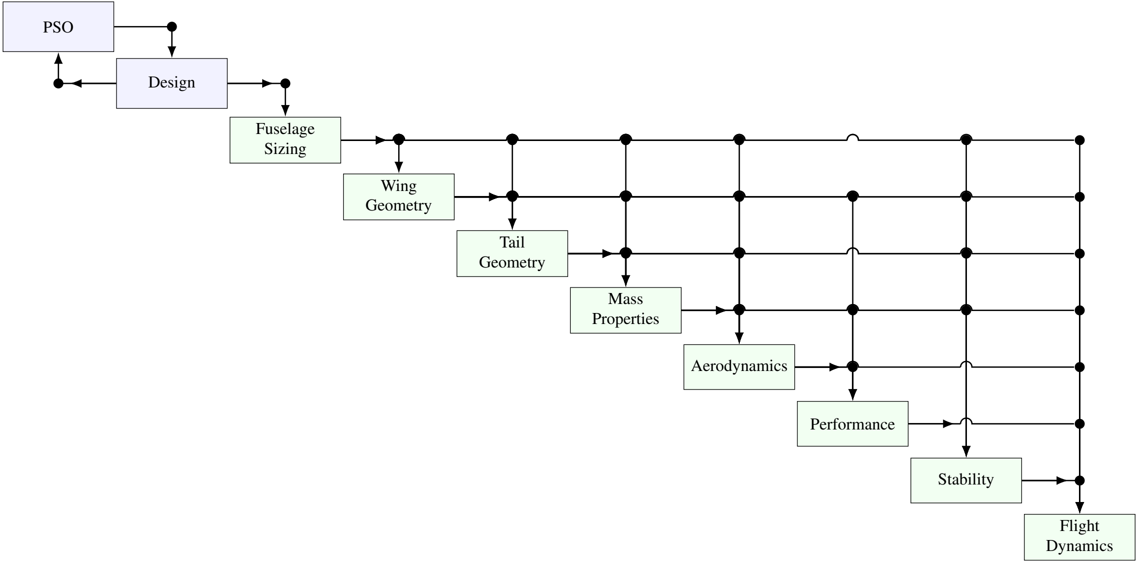
Design parameters:

Discipline	**n vars**
Tail geometry	8
Fuselage	2
Aerodynamics	6
Propulsion	6
Flight control	7
Materials	2
Payload	1
Total	32

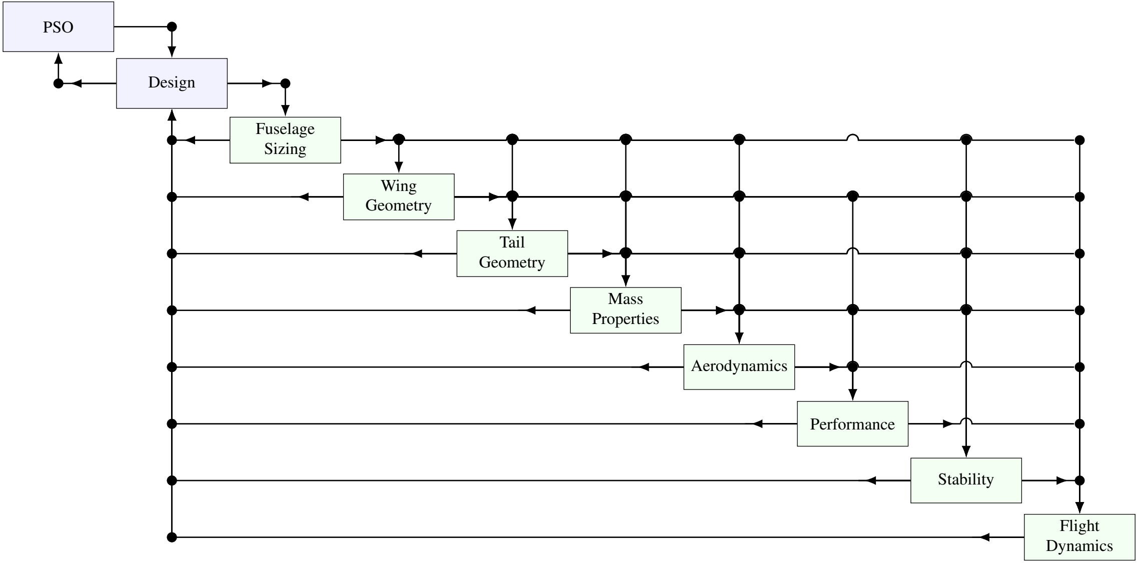
Optimization flowchart



Optimization flowchart



Optimization flowchart



Particle Swarm Optimization (PSO)

Collective behaviour of natural systems Yang, 2010.

The position vector $\mathbf{x_i}$ and the velocity $\upsilon_\mathbf{i}$ for the particle i are utilised to determine the new velocity vector as

$$\upsilon_\mathbf{i}{}^{t+1} = \upsilon_\mathbf{i}{}^{t} + \alpha\varepsilon_\mathbf{1} \odot [\mathbf{b}^* - \mathbf{x_i}{}^{t}] + \beta\varepsilon_\mathbf{2} \odot [\mathbf{x}_\mathbf{i}^* - \mathbf{x_i}{}^{t}], \tag{1}$$

where $\varepsilon_\mathbf{1}$ and $\varepsilon_\mathbf{2}$ are two random vectors that vary between 0 and 1 and the parameters α e β are acceleration constants.

The initial velocity for the particle may be taken as zero $\upsilon_\mathbf{i}{}^{t=0} = 0$.

Then, the new position is updated as

$$\mathbf{x_i}{}^{t+1} = \mathbf{x_i}{}^{t} + \upsilon_\mathbf{i}{}^{t+1}. \tag{2}$$

Reference model

Commercial RPA designed exclusively for research.

Spy Owl 200.

b	2.01 m
$MTOW$	6.5 kg
Endurance	2 hours
H	75-1500 m AGL
$M_{payload}$	2,7 kg
V_{cruise}	14-22 m/s

Adapted from Europe, 2019.

Design requirements

The design requirements:

- the aircraft should be easily transported between operation sites;
- the aircraft should be light enough to be hand-launched;
- the aircraft should be recovered from a belly landing;
- the aircraft should be remotely piloted or to fly autonomously with interference of a human operator;
- the aircraft should transmit the flight data real-time for ground system.

These requirements must be interpreted and transformed into constraints.

Mission and functional requirements

The RPA mission is to carry a research payload with a determined mass utilising electric propulsion.

The functional requirements are:

- Maximum mass of 6.5 kg;
- Maximum span of 2 m;
- Cruise speed of 20 m/s;
- Hand-launched by the operator;
- Recovered by belly landing;
- Operating altitude of 100 m.

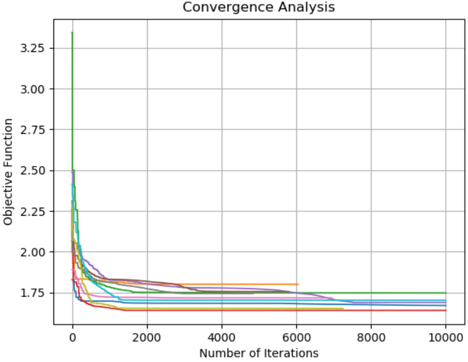
Design variables limits

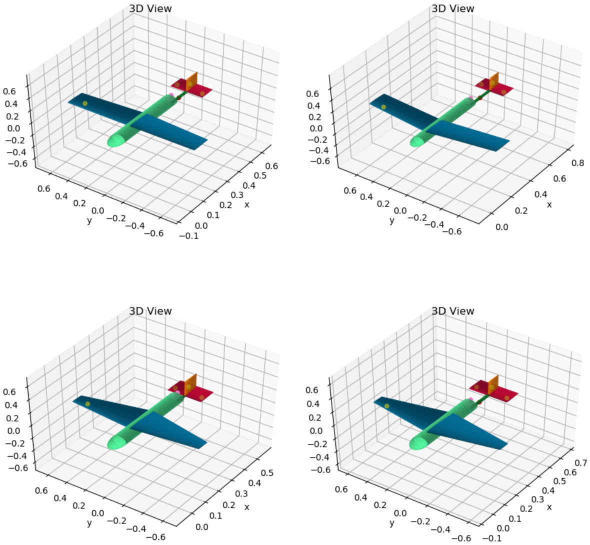
Lower and upper bounds of the design variables of the optimization problem in study.

Nº	Variable	$x_{i,L.B.}$	$x_{i,U.B.}$	Unit
1	AR	6	11	[-]
2	S	0.05	0.5	[m^2]
3	λ	0.3	1	[-]
4	Λ_{LE}	0	10	[deg]
5	x_{r_w}/l_{fus}	0	1	[-]
6	λ_{fus}	3	6	[-]
7	AR_{HT}	3	5	[-]
8	AR_{VT}	1	2.5	[-]
9	$l_{HT}/\bar{c}$	3	6	[-]

Minimization of aircraft structural mass

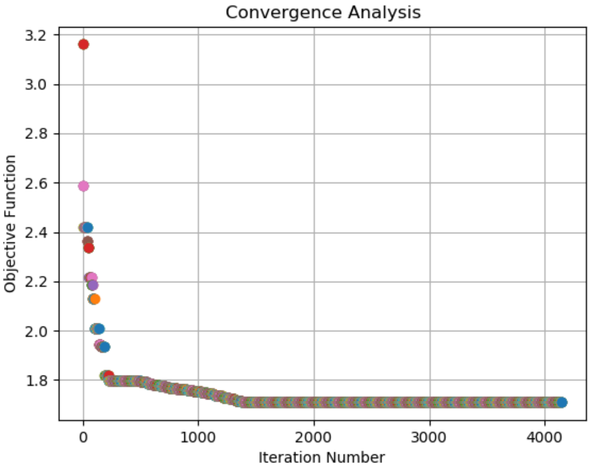
- Evaluate 10 complete runs
- Same input data
- Choose best run





Final concept

- Objective function (total mass) achieved convergence level at 1400 iterations
- Final concept at 4150 iterations
- Convergence: no better value after 1000 iterations



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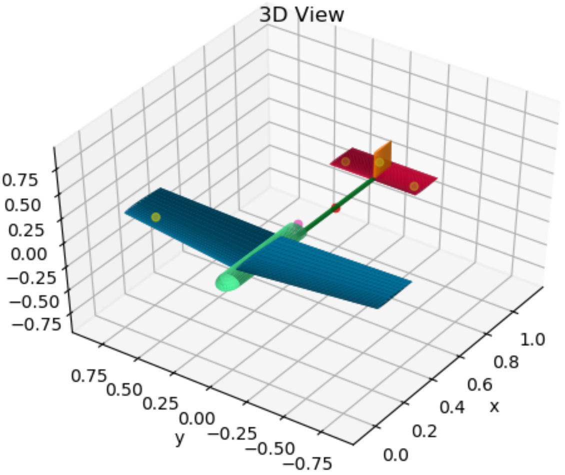
Aircraft configuration at iteration 1.



Final concept

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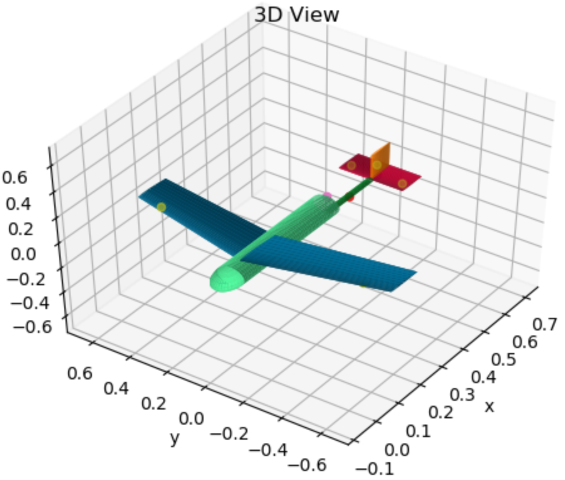
Aircraft configuration at iteration 2000.



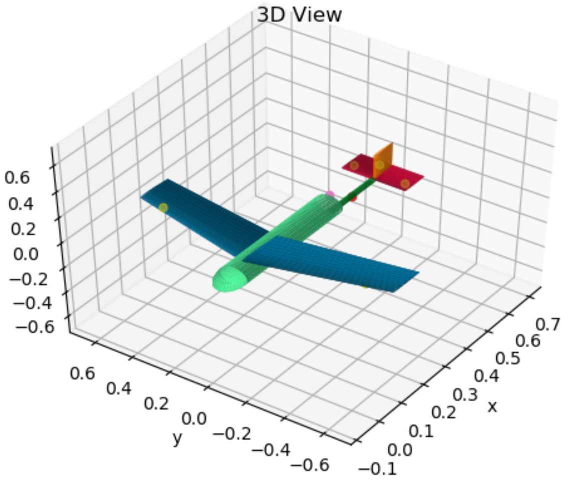
Final concept

- Objective function (total mass) achieved convergence level at 1400 iterations

- Final concept at 4150 iterations

- Convergence: no better value after 1000 iterations

Aircraft final configuration at iteration 4150.



Final concept - design variables

Optimized design variables :

Variable	x_{gbest}	Unit
AR	9.67	
S	0.17	[m^2]
λ	0.77	
Λ_{LE}	8.47	[deg]
x_{r_w}/l_{fus}	0.13	
λ_{fus}	3	
AR_{HT}	3.69	
AR_{VT}	2.17	
$l_{HT}/\bar{c}$	3.87	

Final concept - design variables

Optimized design variables :

Variable	x_{gbest}	Unit
AR	9.67	
S	0.17	$[m^2]$
λ	0.77	
Λ_{LE}	8.47	[deg]
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λ_{fus}	3	
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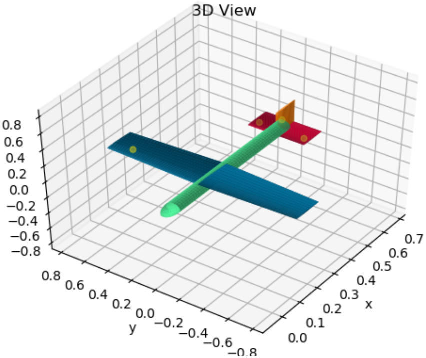
Design with $5 \leq \lambda_{fus} 7$



Final concept - output data

Parameter	Value	Unit
Mass properties		
M_{tot}	1.71	[kg]
Aerodynamics		
i_w	3.23	[deg]
i_{HT}	1.31	[deg]
C_{D_0}	0.055	
k	0.041	

Parameter	Value	Unit
Performance		
E	36	[min]
R	44	[km]
Stability		
C_{m_α}	-0.584	[1/rad]
C_{n_β}	0.0	[1/rad]
C_{l_β}	-0.079	[1/rad]
C_{y_β}	-0.412	[1/rad]
SM	12.5	[%]

- Diverse aeronautical engineering disciplines (aerodynamics, stability, flight dynamics, etc.) are coupled into a single driver code that handles all design information;
- Considering constraints of RPA missions using known general aviation methodologies is still a challenging task;
- The process requires experience to establish constraints and bounds
- This is an ongoing development work. The disciplines analyses are implemented in Python language in form of independent packages, called by the main code.
  - ◇ New disciplines can be easily added or the ones already present can be improved.
  - ◇ The same approach is applicable to the optimization method, once the RPA design code is also a module to be called in the routine.

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