# Control-aware Design of the Combined Geometric and Structural Properties of an Underwater Kite

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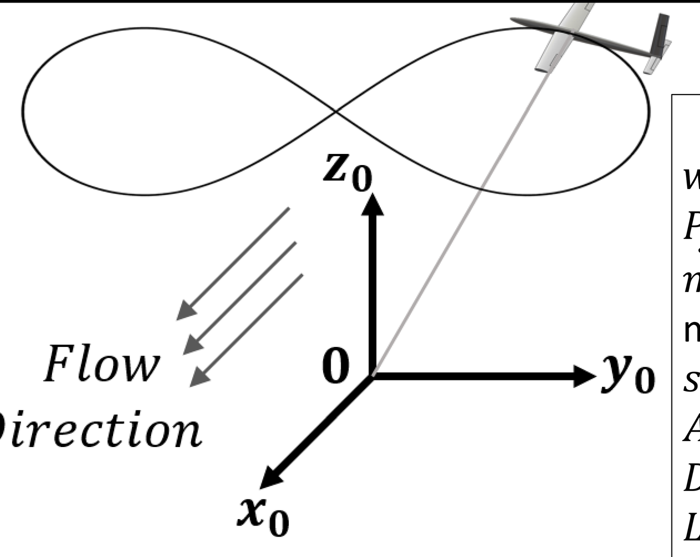
## Kite system

- Controlled cross-current flight achieved through tracking a figure-8 path.
- Spooling operation: High-tension spool-out (large power generation) and low-tension spool-in (small power consumption) = net power generated.




**Co-design Objective:** Simultaneous optimization of controller and plant (kite geometry and structure).

## Overall optimization problem

Objective: $\max_{\boldsymbol{u}} \; P_{gen}^{w_1} - m_{kite}^{w_2}$

Subject to: $P_{gen}(\boldsymbol{u}) \geq P_{req}$ (performance constraint)

$I_{xx}(\boldsymbol{u}) \geq I_{xx,req} \mid \delta_{max}$ (wing structural constraint)

$C_f(\boldsymbol{u}) \geq 0$ (fuselage structural constraint)

$\rho V_{kite} \geq m_{kite}$ (kite buoyancyconstraint)

$\boldsymbol{u} \in \{s, AR, D, L, N_{sp}, t_{sp}, t_{sh,w}, t_{sh,f}\}$

**Idea:** Maximizing $P_{gen}$ and minimizing $m_{kite}$ are two important technical metrics. $w_1, w_2$ allow incentivizing one over the other.

**Special case**: $w_1 = w_2$, objective maximizes $P_{gen}/m_{kite}$ (power-to-weight ratio), an accepted techno-economic metric.

**Variables**

- $w_1, w_2$ = realtive weights
- $P_{gen}$ = generated power
- $m_{kite}$ = kite structural mass
- $s$ = wingspan
- $AR$ = wing aspect ratio
- $D$ = fuselage diameter
- $L$ = fuselage length
- $N_{sp}$ = No. of spars
- $t_{sp,i}$ = thickness of i$^{th}$ spar
- $t_{sh,w}$ = wing shell thickness
- $I_{xx}$ = Principal moment of inertia about x axis
- $\delta_{max}$ = max. wing tip deflection
- $TR$ = wing taper ratio
- $\phi_w$ = wing twist
- $\psi_w$ = wing dihedral
- $x_{spi}$ = location of i$^{th}$ spar
- $\alpha$ = angle of attack
- $t_{sh,f}$ = fuselage shell thickness

## Optimization Modules

Overall optimization problem divided into 3 sub-problems.

**Steady Flight Optimization Tool (SFOT)**

Selects wing and stabilizer geometric properties to maximize the kite's flight performance. Relevant variables: $s, AR, D, L$

**Structural Wing Design Tool (SWDT)**

Selects spar and skin properties to minimize wing mass, subject to wing tip deflection and buoyancy considerations. Relevant variables: $s, AR, N_{sp}, t_{sp}, t_{sh,w}$

**Structural Fuselage Design Tool (SFDT)**

Selects fuselage thickness to minimize fuselage mass, subject to hoop stress, sheer stress, and buckling constraints. Relevant variables: $D, L, t_{sh,f}$

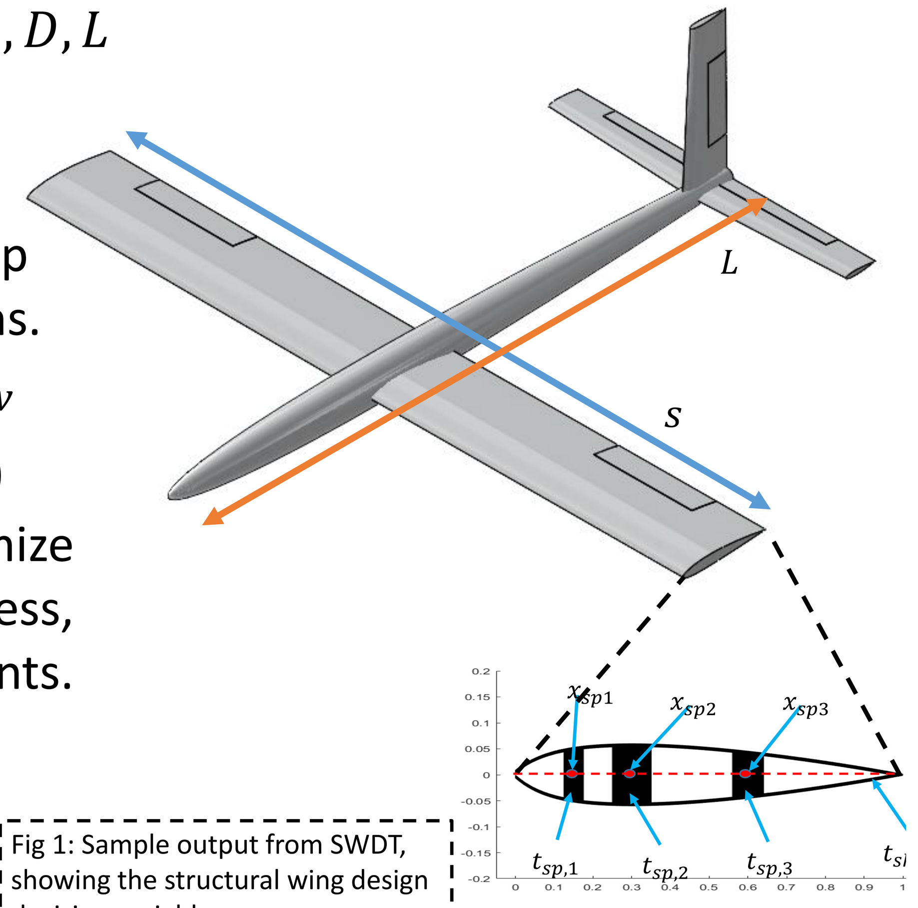
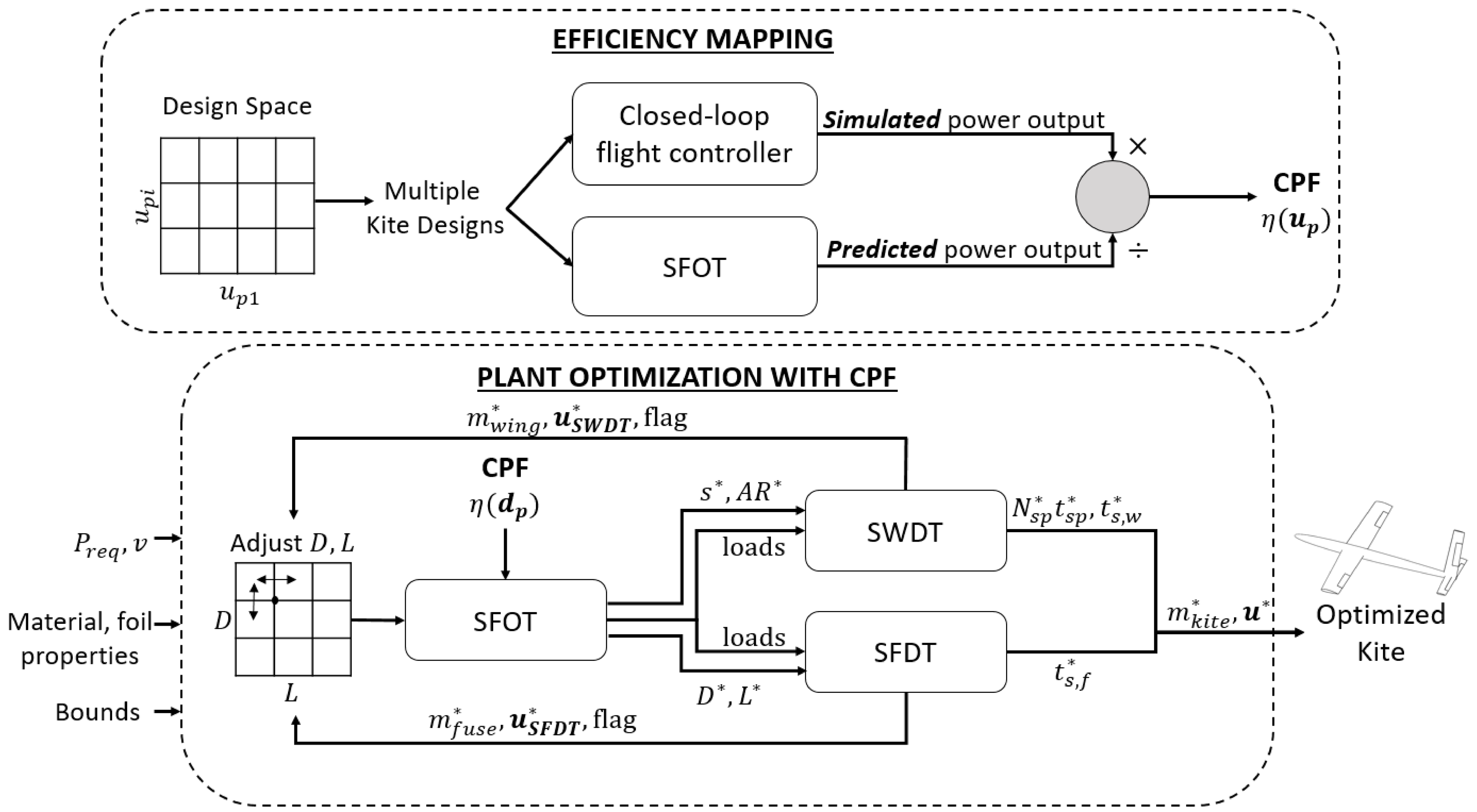



Fig 1: Sample output from SWDT, showing the structural wing design decision variables.

## Co-Design Framework




## Control Proxy Function(CPF): $\eta$ mapping

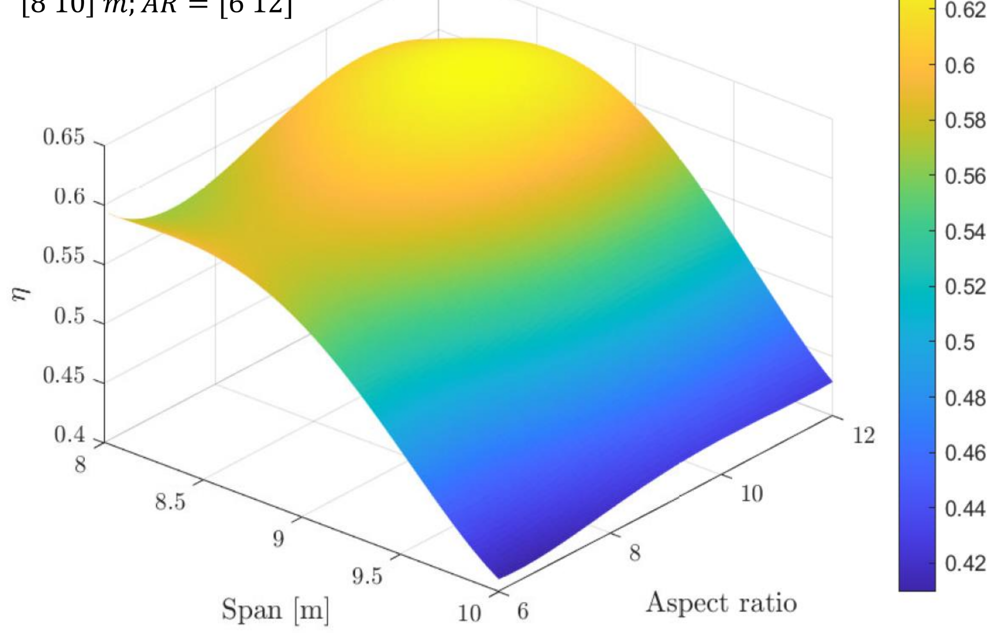
**Approach**: Simulate multiple kite designs within the design space and map $\eta$ to obtain $\eta(\boldsymbol{u_p})$, where $\boldsymbol{u_p} \in \{s, AR\}$ are plant decision variables that directly affect flight performance.

- $\eta$ term in (1) accounts for losses due to spooling and dynamic flight.

$$P_{gen} = \eta \cdot \left(\frac{2}{27}\right) \rho S_{ref} v^3 \left(\frac{C_L^3}{C_D^2}\right)$$

- Accounts for closed-loop flight performance, as $\eta$ acts as a CPF, **making the system control-aware.**
- Allows the optimization to run without the need to simulate the design with the closed-loop controller in the loop, **significantly reducing computational cost.**

Fig 2: CPF. Design space $s$ = [8 10] $m$; $AR$ = [6 12]

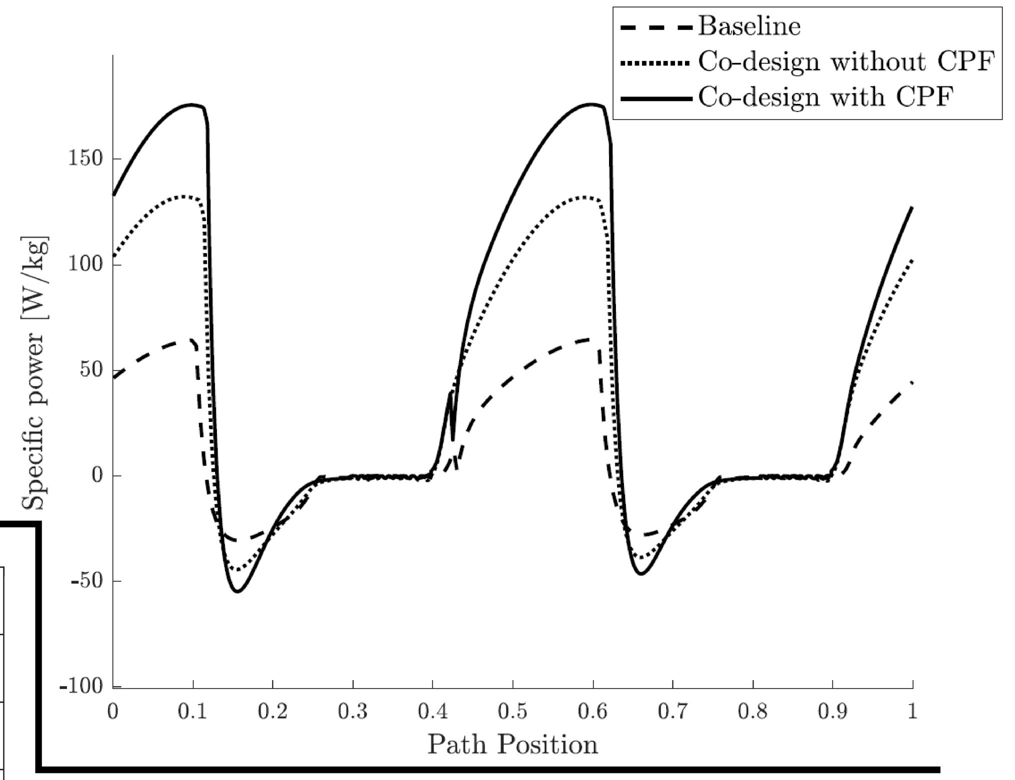


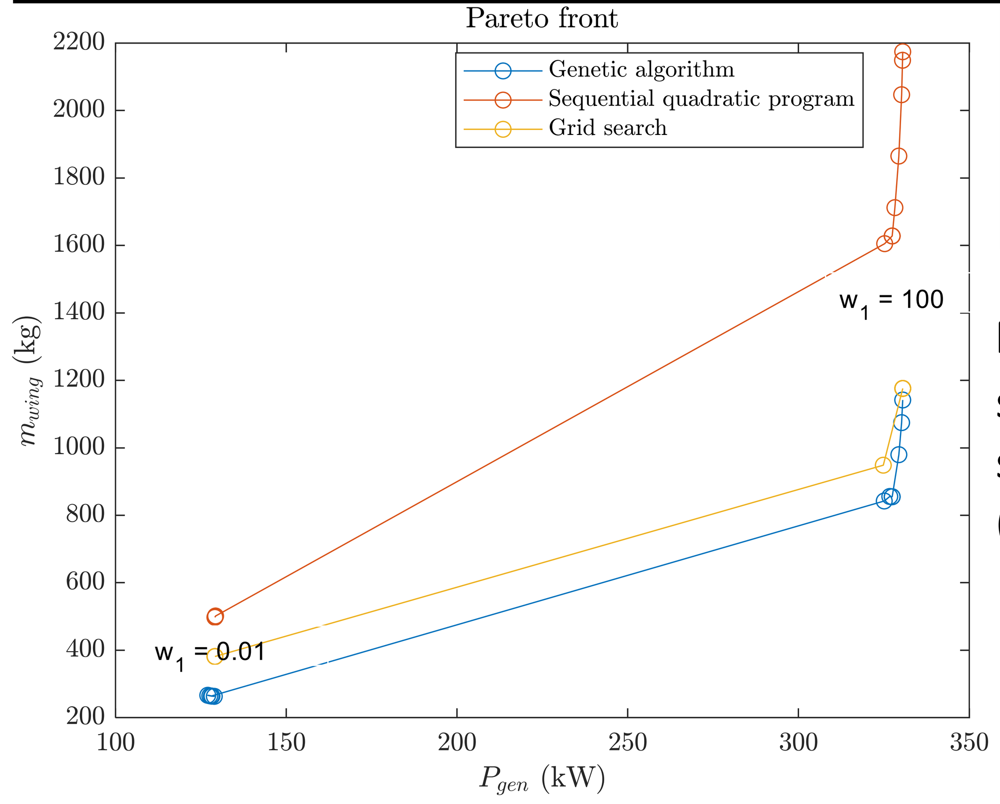

## Co-Design Results

**Objective:** Maximize Power-to-Weight ratio

**Results:**

1. Baseline → Optimized without CPF: 111% improvement in specific power!
2. Optimized without CPF → Optimized with CPF: 22% improvement in specific power!




**Pareto Front:** Resulting $P_{gen}$ and $m_{kite}$ of solving the overall optimization problem simultaneously for different relative weights ($w_1$ varied, $w_2 = 1$).

## Future work: Higher fidelity wing design

**Idea:** Increase fidelity of modeling by adding more decision variables (listed below) that are used to define:

1. Wing geometry: $TR, \phi_w, \psi_w$, type of airfoil
2. Wing structure: $t_{sp,i}, x_{spi}$

**Implications and modeling:**

1. Wing geometry: Effects of changing wing geometry is capture through analysis in XFLR5. Hydrodynamic coefficients estimated within the design space are used to form a look-up table for the optimization.
2. Structural effects of changing position and thickness of spars and varying cross section due to taper ratio are captured in the structural tool.

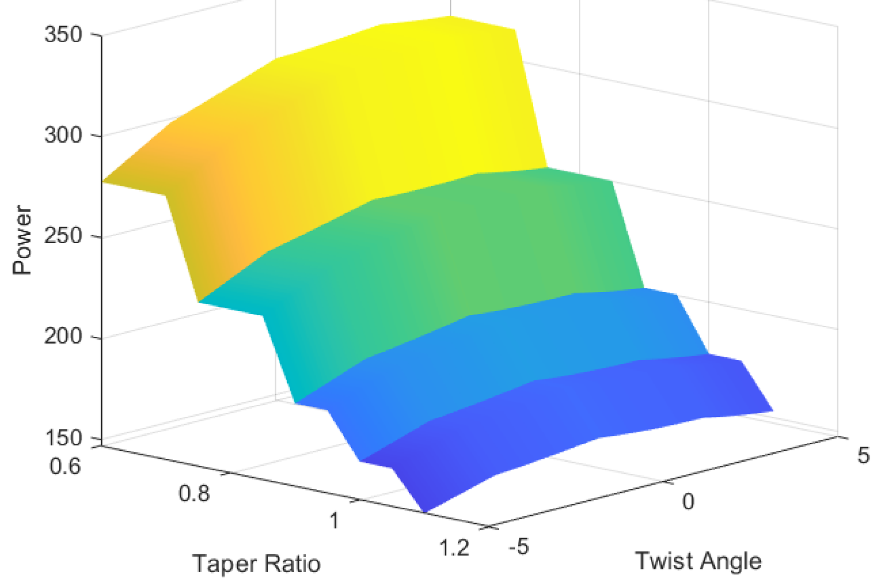



Fig 3: Effect of wing twist [deg] and taper ratio to $P_{gen}$.

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