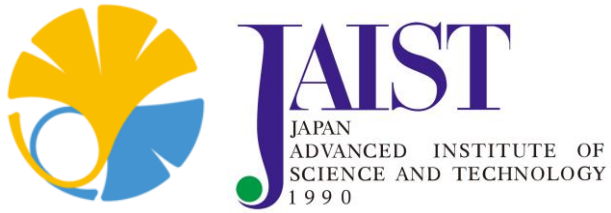
Precomputed Panel Solver for Aerodynamics Simulation

Haoran Xie
The University of Tokyo / JAIST



Aerodynamics Simulation

for Graphics and Fabrication

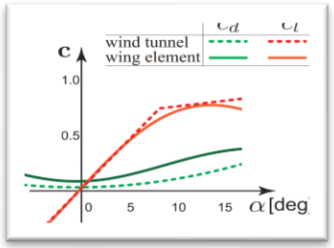
J. Wejchert. SIGGRAPH91

E. Ju, et al., SIGGRAPH14

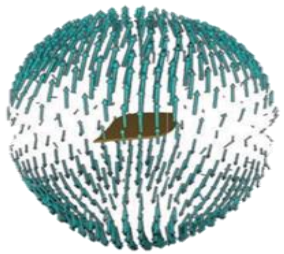
T. Martin, et al., SIGGRAPH15

Aerodynamics in Graphics

Data-Driven

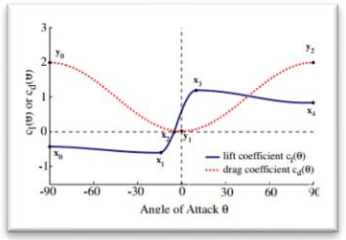


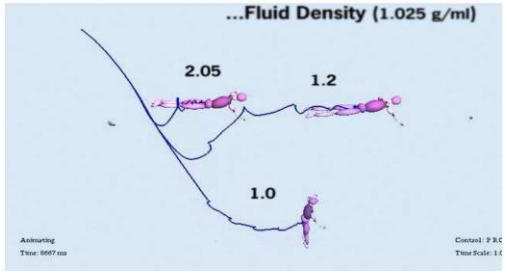
@N.Umetani, et al, TOG2014



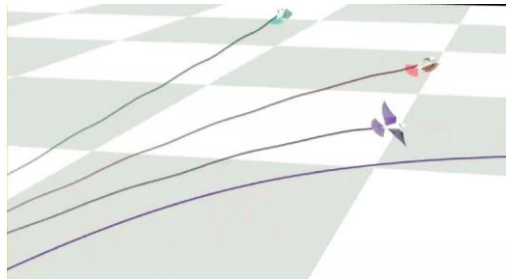
@T.Martin, et al, TOG2015

Heuristic Method



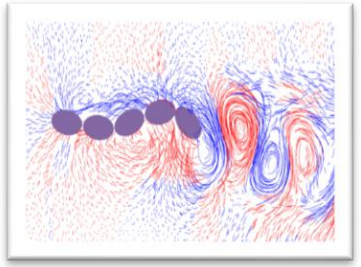


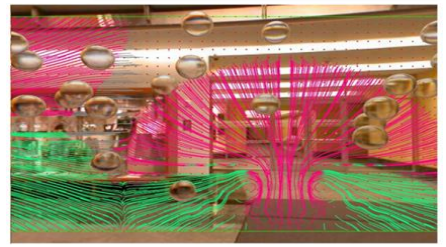
@P.Yang, et al, SCA2014



@E.Ju, et al, TOG2013

Coupling Based





@X.Wei, et al, SCA2013

@J.Tan, et al, TOG2011

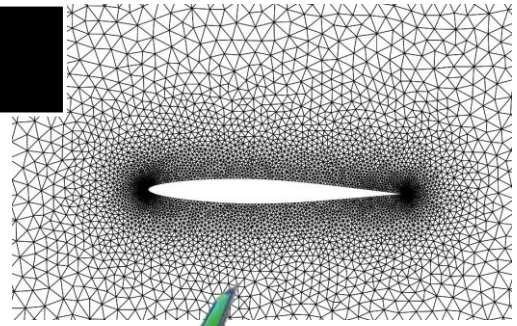
Simplified Model

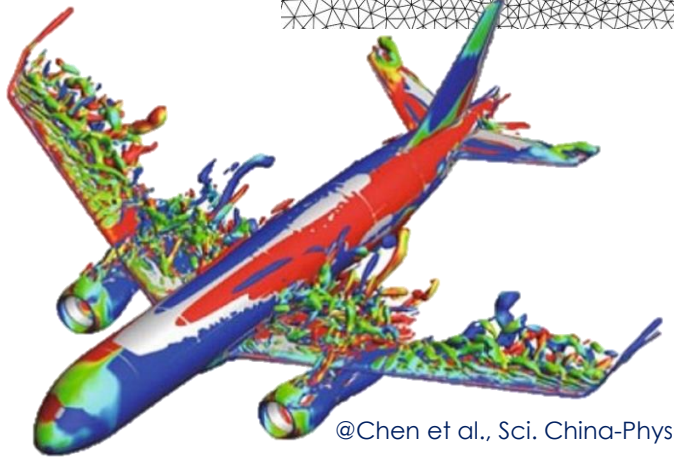
Low Accuracy

Heavy Computation

Aerodynamics in Engineering

Grid-Based

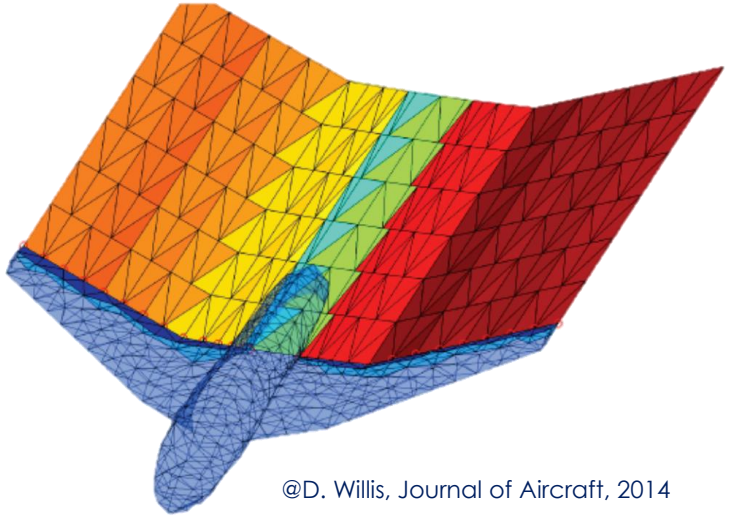




@Chen et al., Sci. China-Phys. Mech. Astron., 2013.

Heavy Computation

Singularity-Based

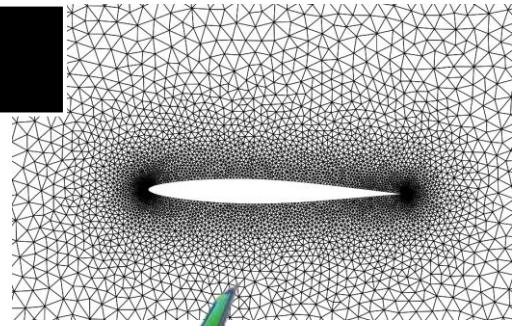


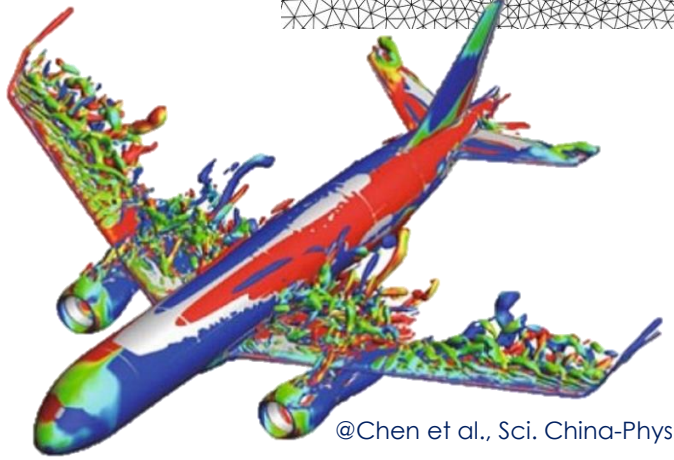
@D. Willis, Journal of Aircraft, 2014

Low Cost and Good Accuracy

Aerodynamics in Engineering

Grid-Based



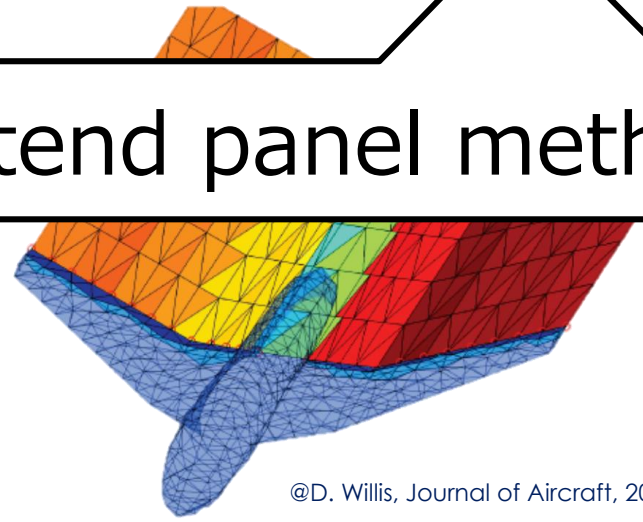


@Chen et al., Sci. China-Phys. Mech. Astron., 2013.

Heavy Computation

Singularity-Based

We extend panel method !



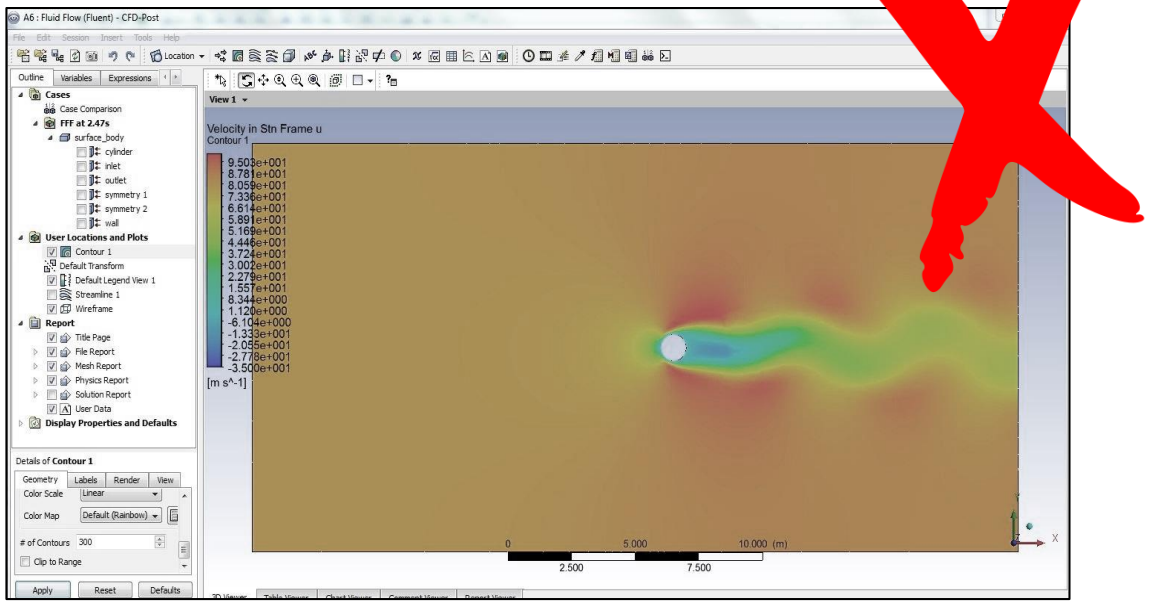
@D. Willis, Journal of Aircraft, 2014

Low Cost and Good Accuracy

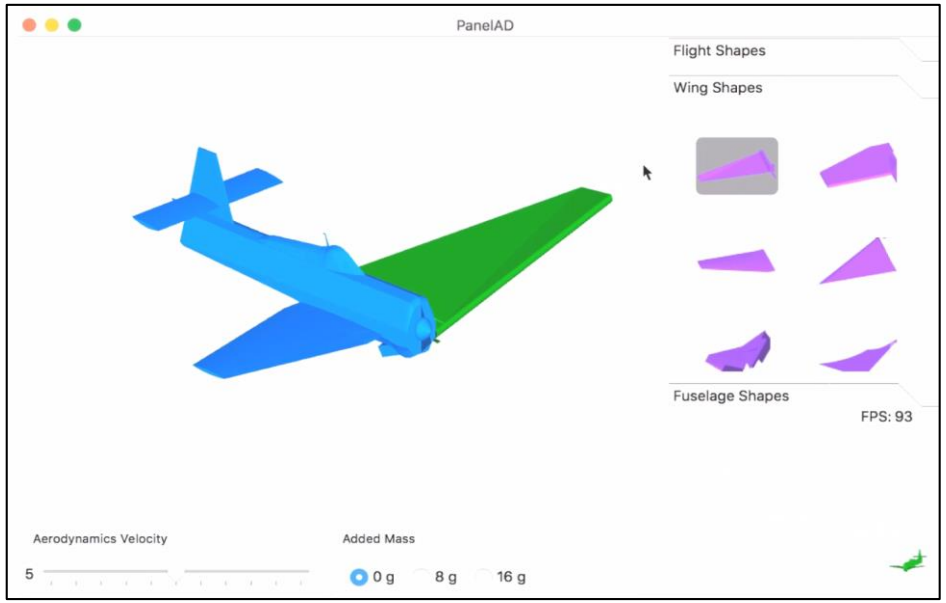
Motivation

Our goal is to create a **fast aerodynamic simulation algorithm,** enabling designers to **design gliders with interactive feedbacks.**

@ANSYS Fluent CFD Tutorial



CFD tools

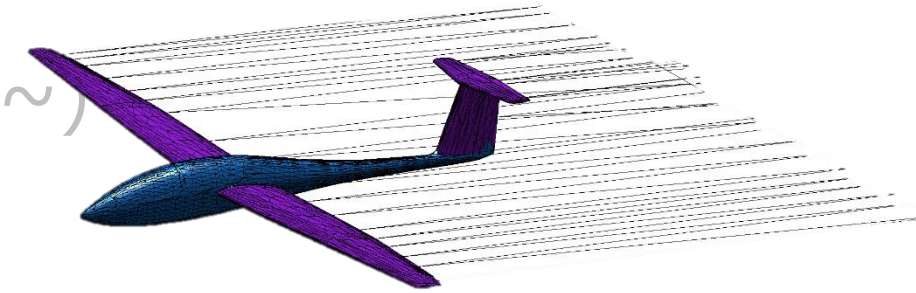


our work

Computational Framework

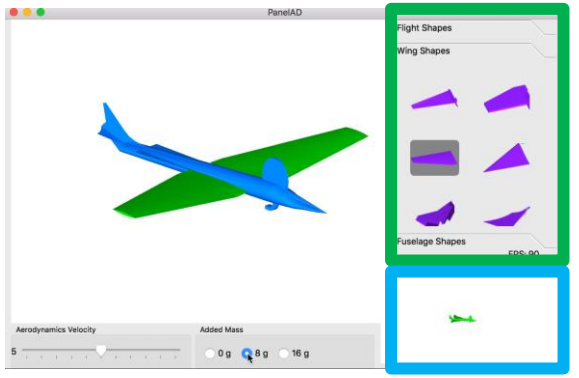
Aerodynamics Simulation Algorithm

- Precomputed panel method (x10,000~)
- Interactive simulation pipeline



Interactive Glider Design System

- Assembly-based user interface
- Glider design and fabrication



Computational Framework

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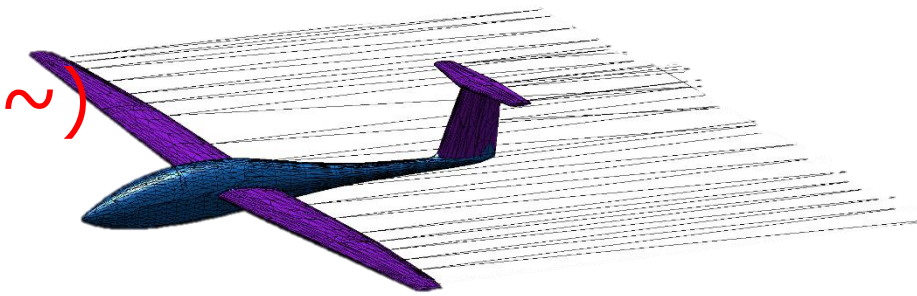

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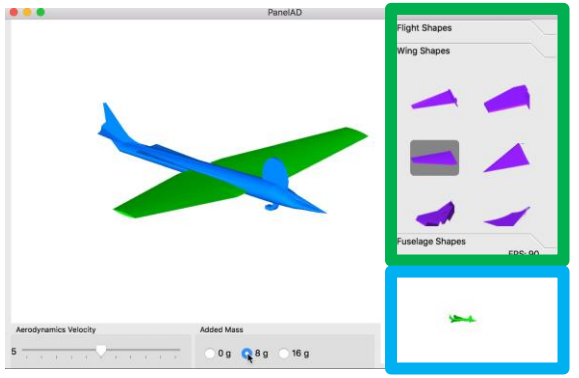
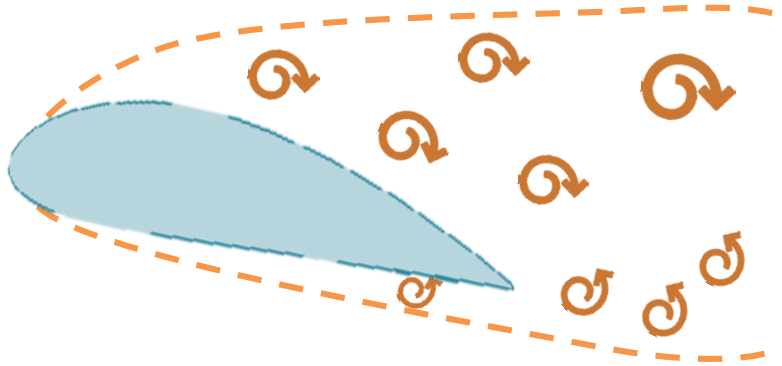
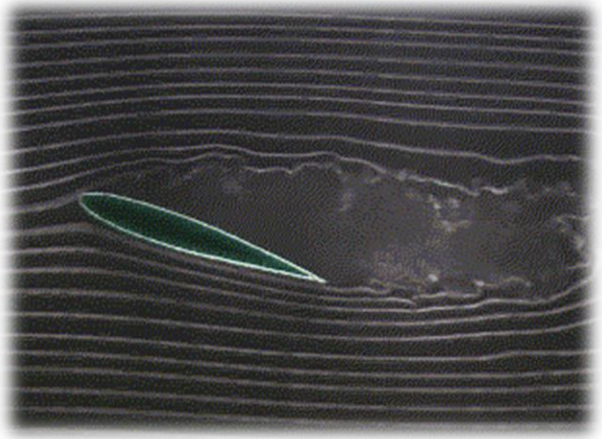


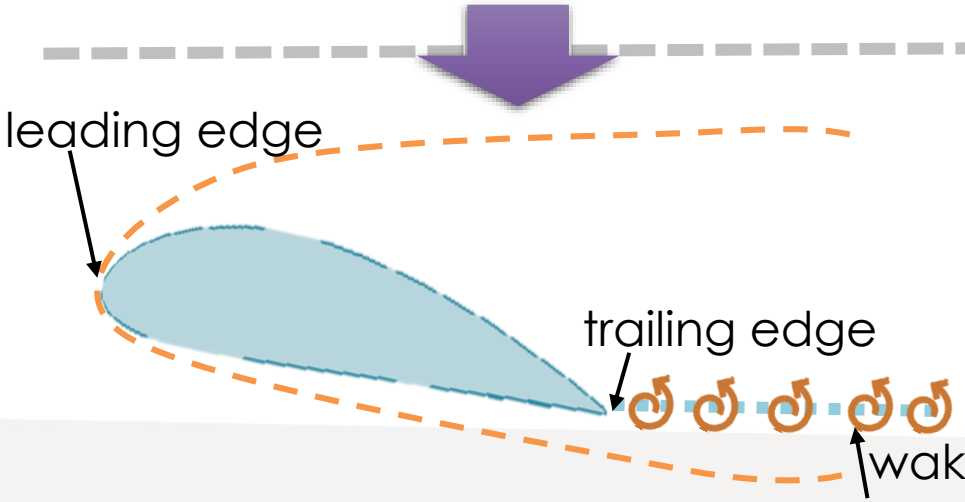
Flow Assumption

airflow



Real Flow:
turbulent, unsteady

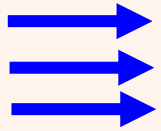




Potential Flow:
inviscid, incompressible

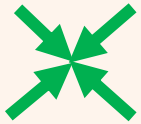
@Marine Hydrodynamics, MIT Lectures

Flow Elements



Uniform

Source

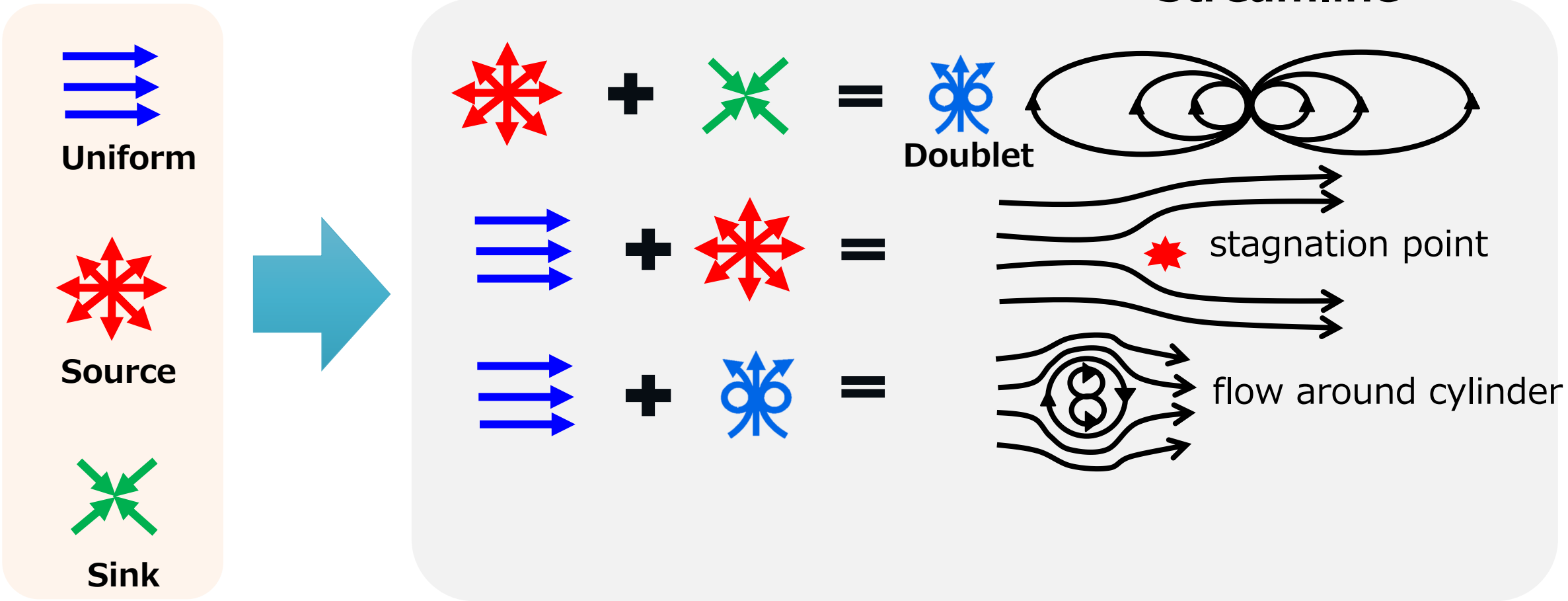


Sink

Basic Elements

Flow Elements

Streamline



Flow Elements

Streamline

Uniform

Source

Sink

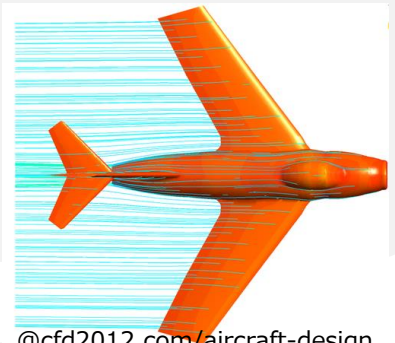
Basic Elements

Doublet

stagnation point

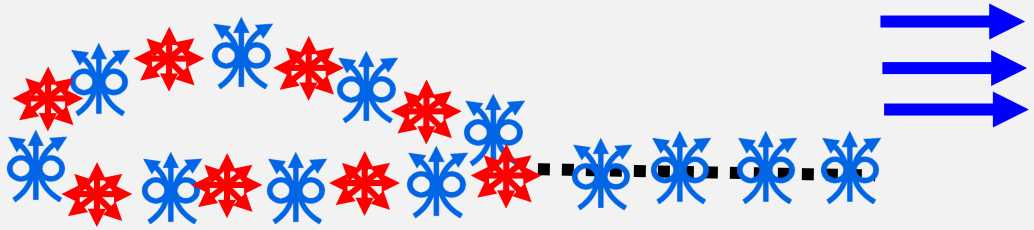
flow around cylinder

Superposition



@cfd2012.com/aircraft-design

Panel Method [Hess and Smith, 1967]



i : element index

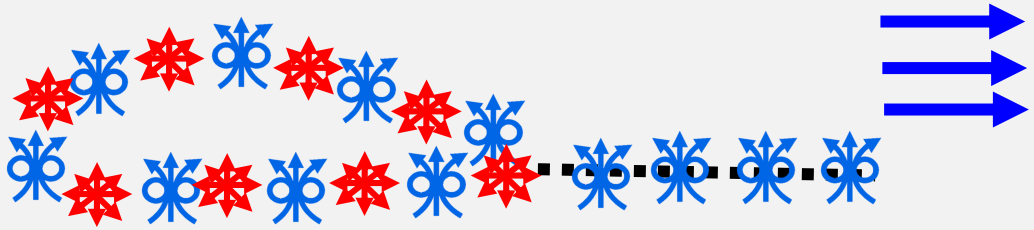
Doublet

$$\Phi_d^i = \frac{\partial \Phi_s}{\partial n} = \int_{\partial B} \mu \frac{\partial}{\partial n}\left(\frac{1}{r}\right) ds$$

doublet strength

Panel Method [Hess and Smith, 1967]

i : element index



$$\Phi_d^i = \frac{\partial \Phi_s}{\partial n} = \int_{\partial B} \mu \frac{\partial}{\partial n}\left(\frac{1}{r}\right) ds$$

Doublet

doublet strength

Green's Identity:

$$\Phi = \Phi_d - \Phi_s$$

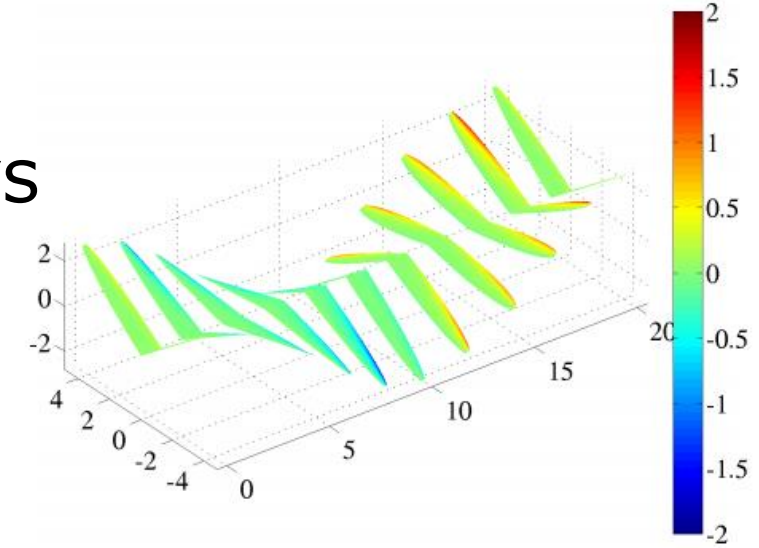
velocity potential (~ body state)

(~ doublet strengths U)

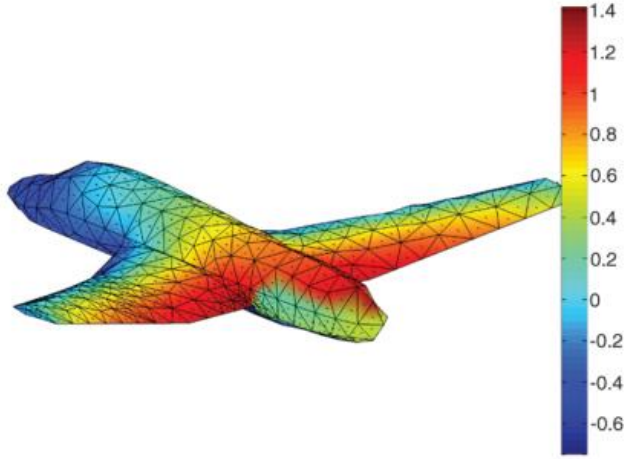
fixed

Panel Method

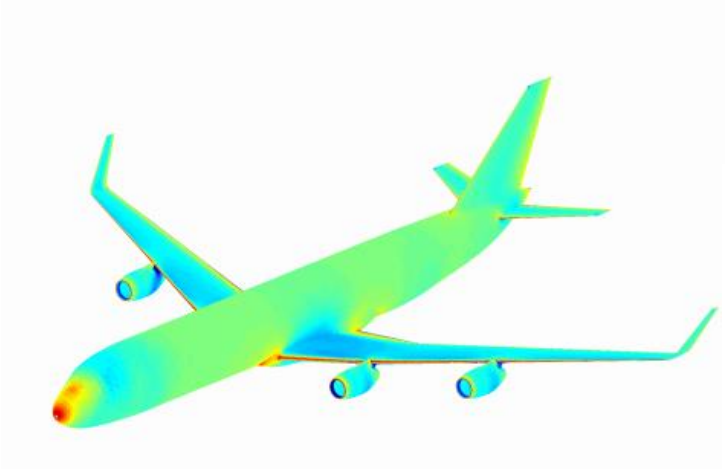
- Why we still need panel solver nowadays
  - Fast, Robust, Accurate in aircraft design
  - Suitable for many applications



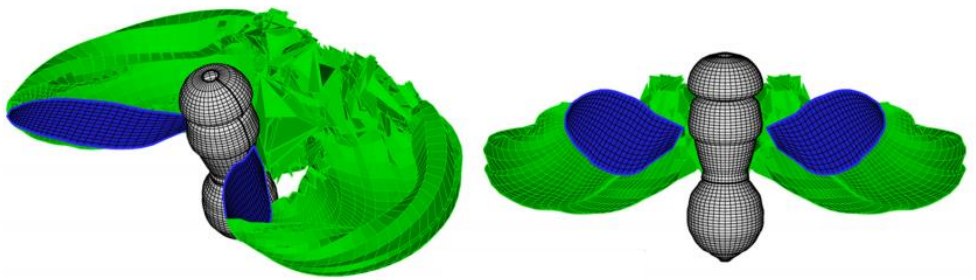
[AIAA conference, 2010]



[Journal of Aircraft, 2014]



[AIAA conference, 2013]

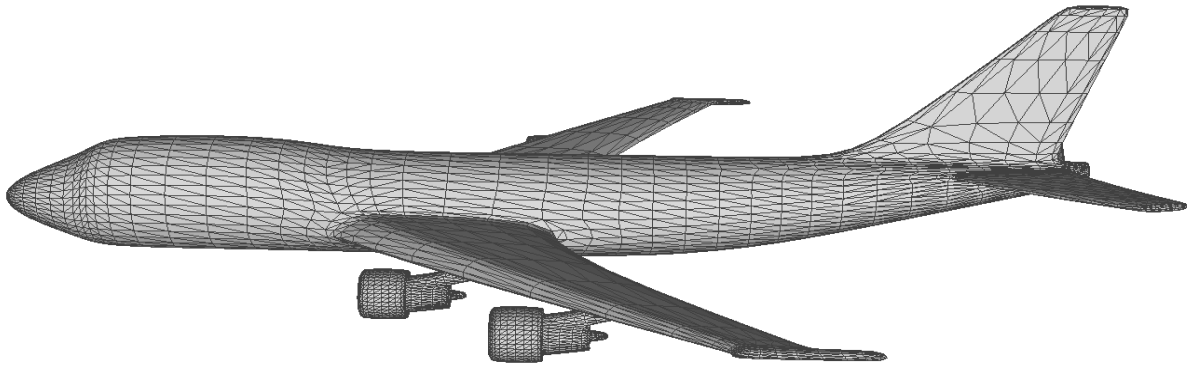


[AIAA Journal, 2013]

Computation Issue

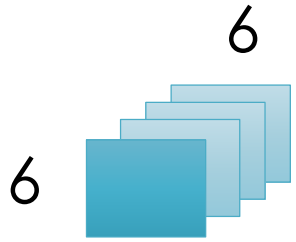
for each frame:

Standard Panel Method: 400 seconds



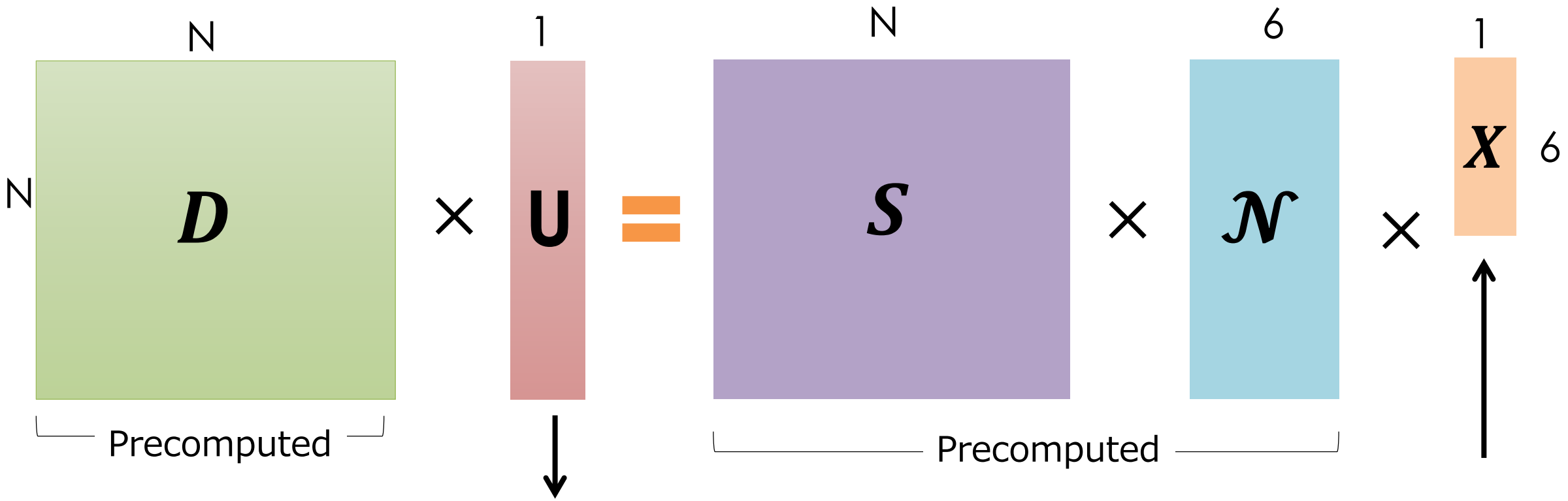
※ mesh size: N= 6000

?



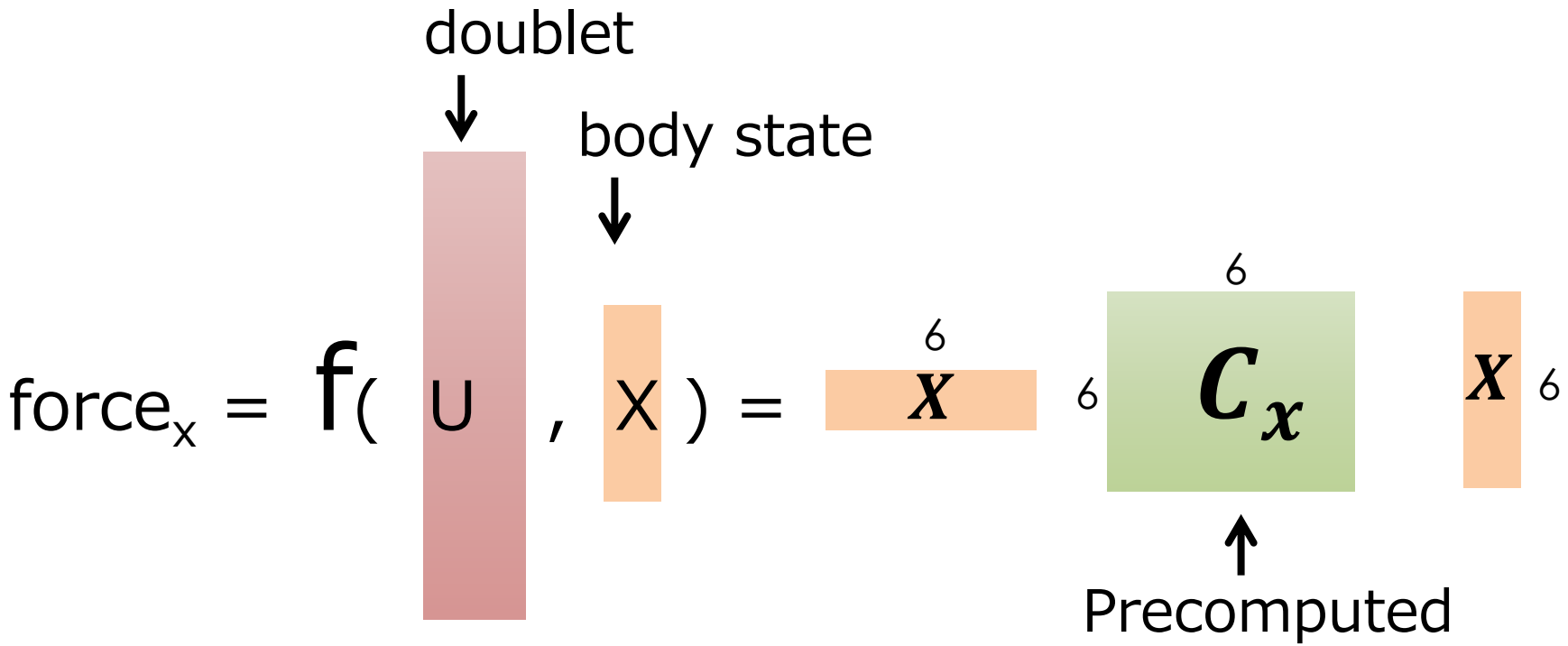
Interactive design: 0.01 seconds

Body State → Doublet



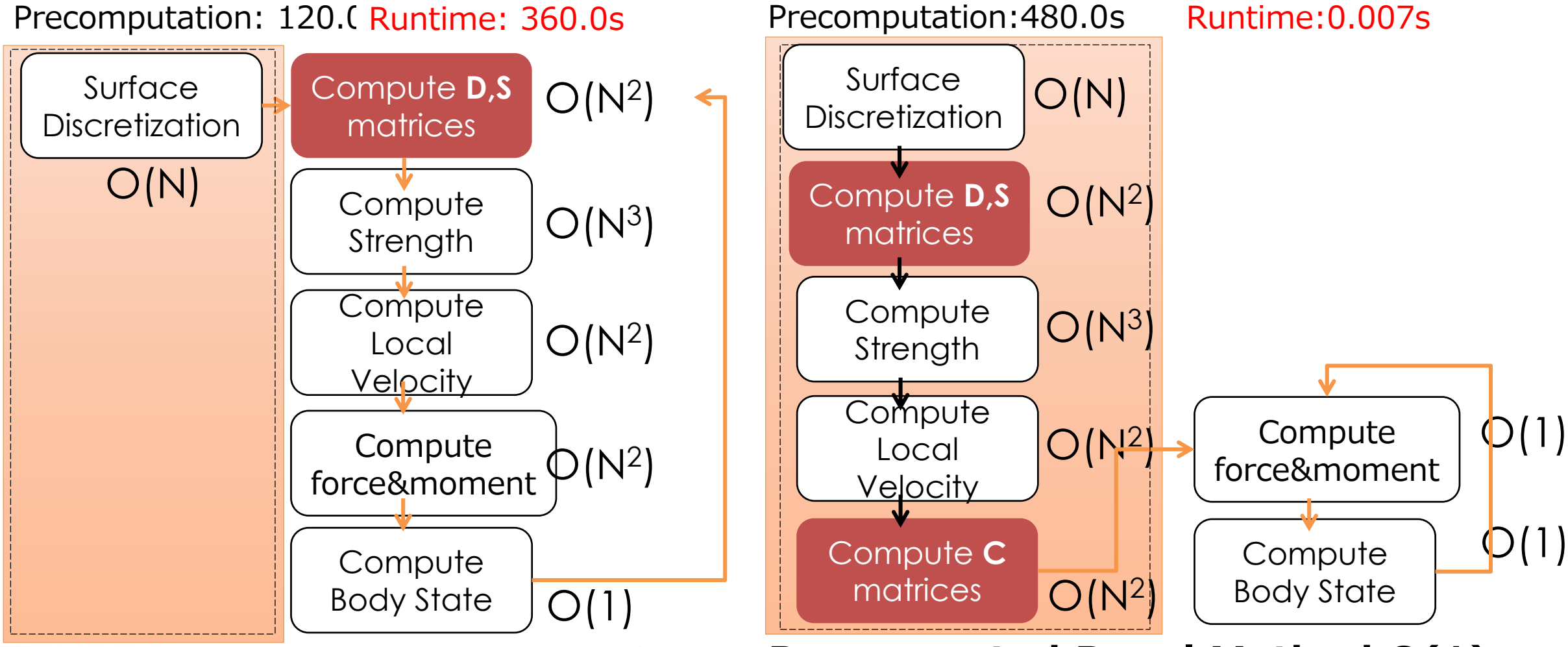
※ N: mesh size

Doublet → Force

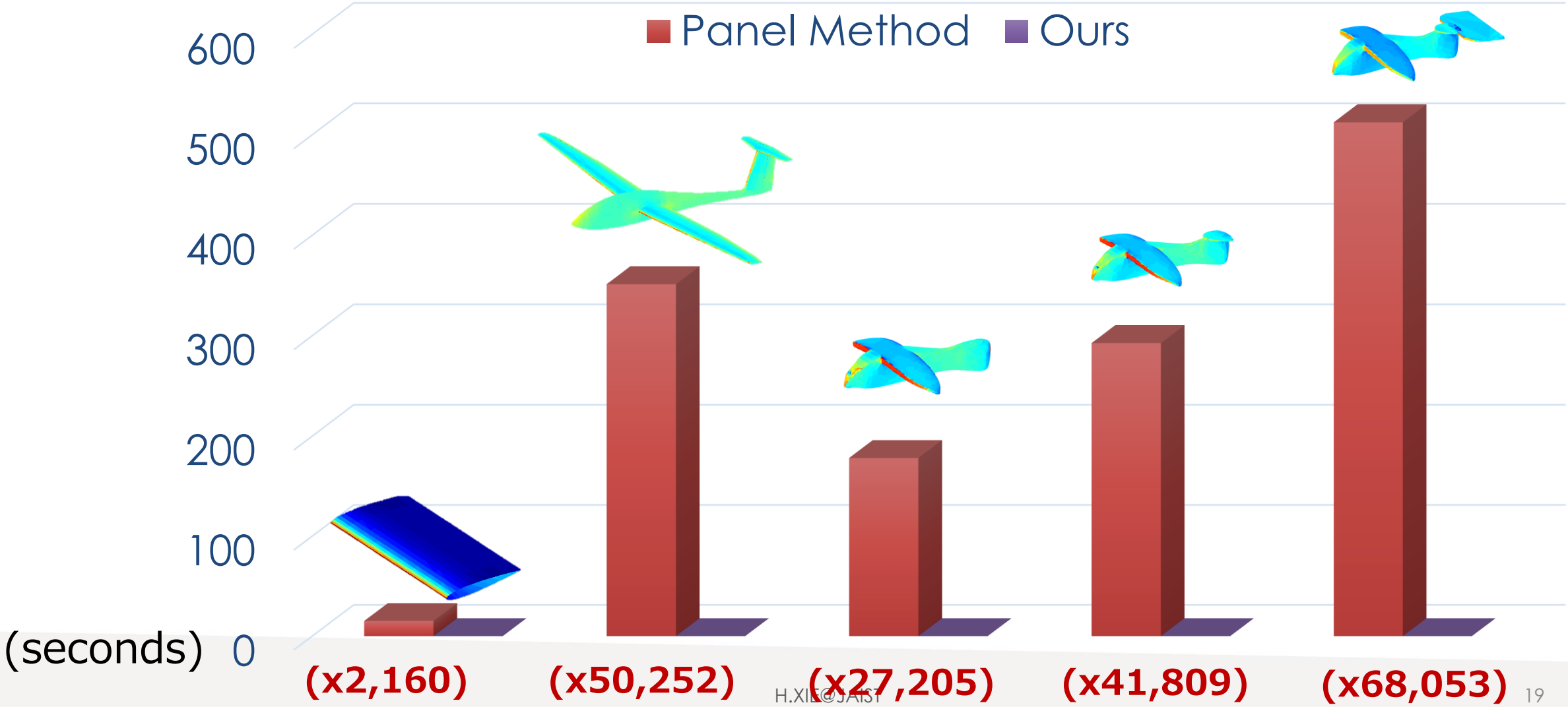


(※ we compute torque in similar way)

Precomputed Process



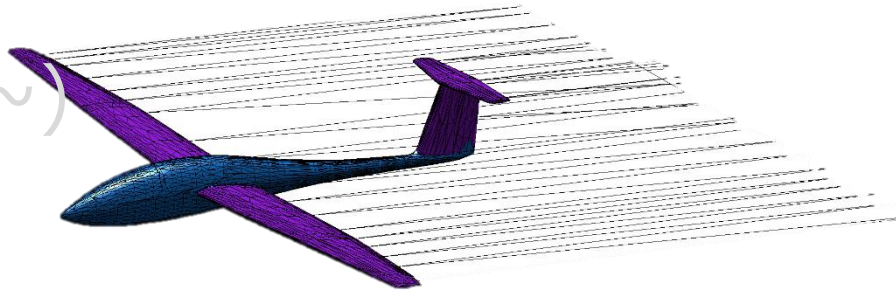
Computation Cost



Computational Framework

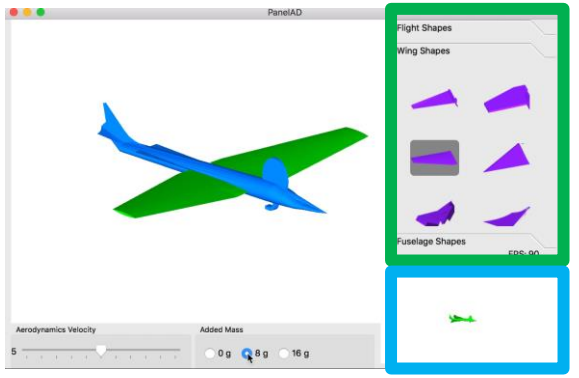
Aerodynamics Simulation Algorithm

- Precomputed panel method (x10,000~)
- Interactive simulation pipeline

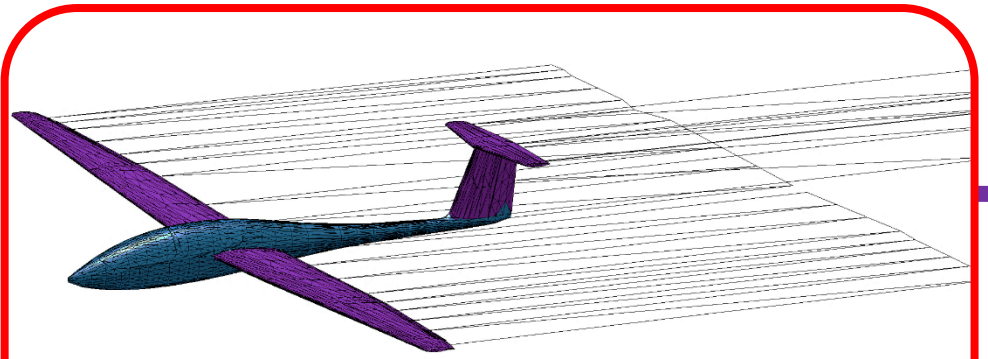


Interactive Glider Design System

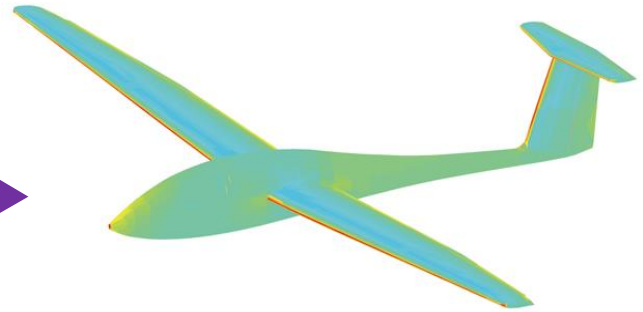
- Assembly-based user interface
- Glider design and fabrication



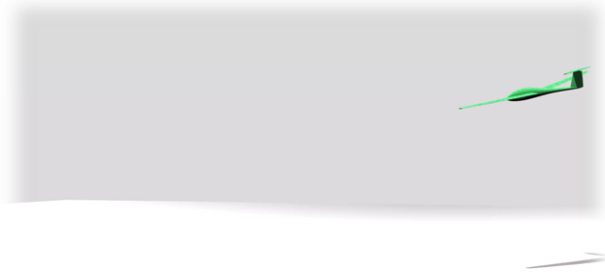
Full Simulation pipeline



Geometry Preprocessing



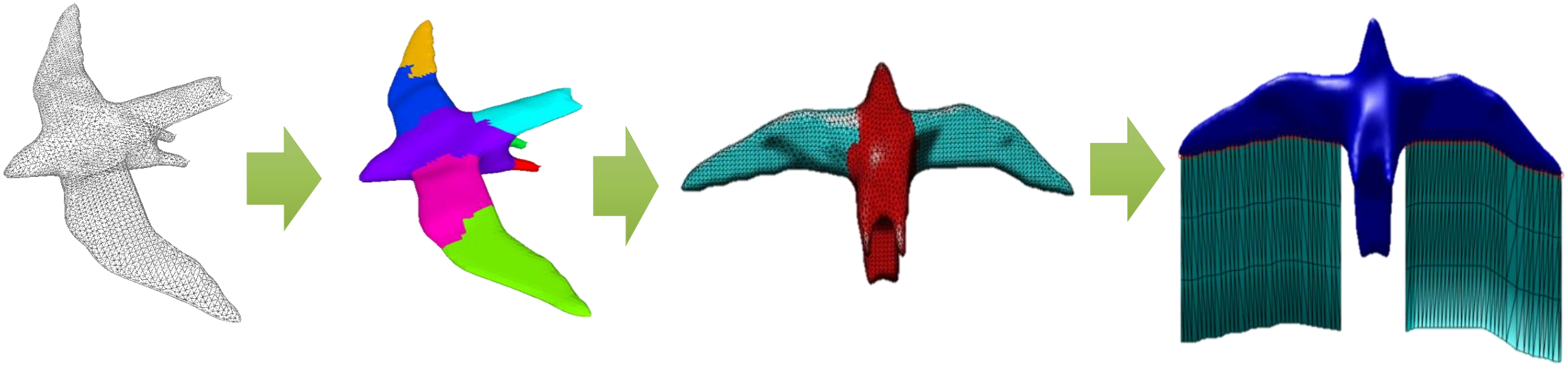
Aerodynamics Precomputation



pre-computation

runtime

Geometry Preprocessing



input

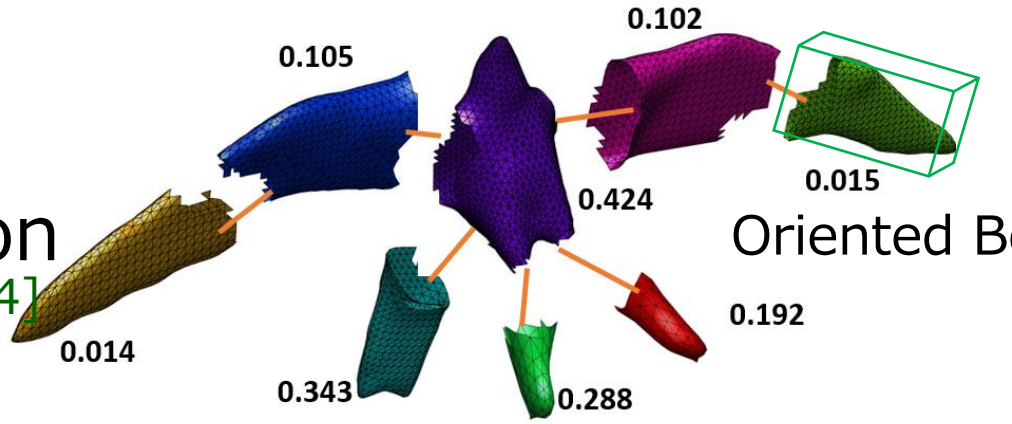
mesh segmentation

wing recognition

wake-panel generation

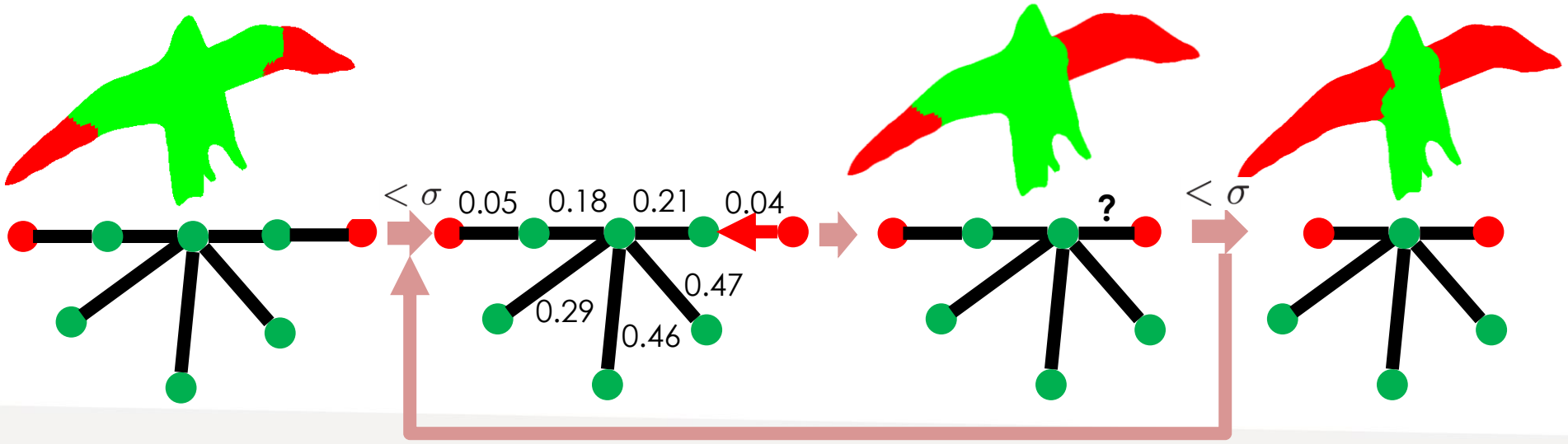
Wing Recognition

Mesh Segmentation:
→ convex shape decomposition
[O. Kaick et al, TOG2014]

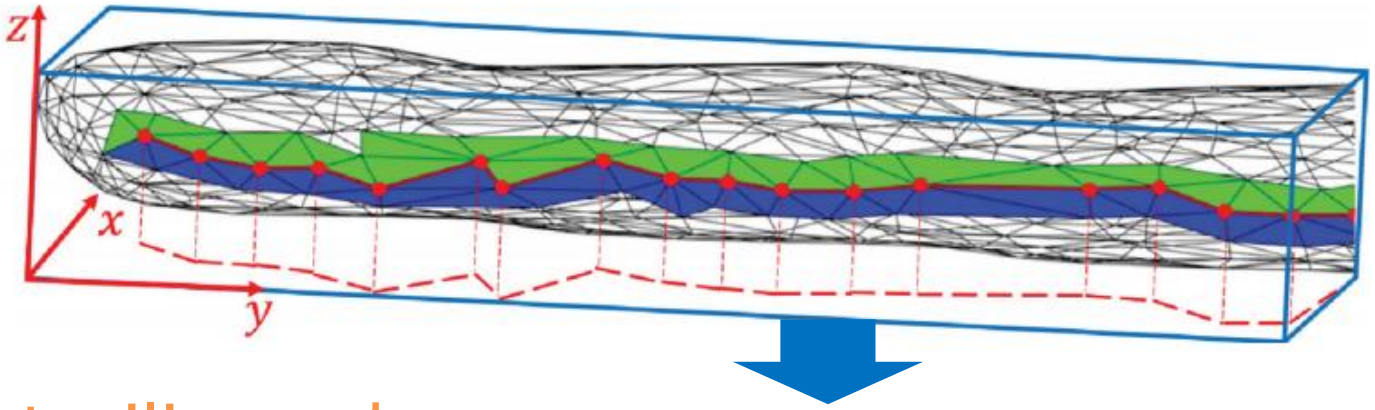


Oriented Bounding Box

Extracting wing parts:
→ bottom-up clustering process

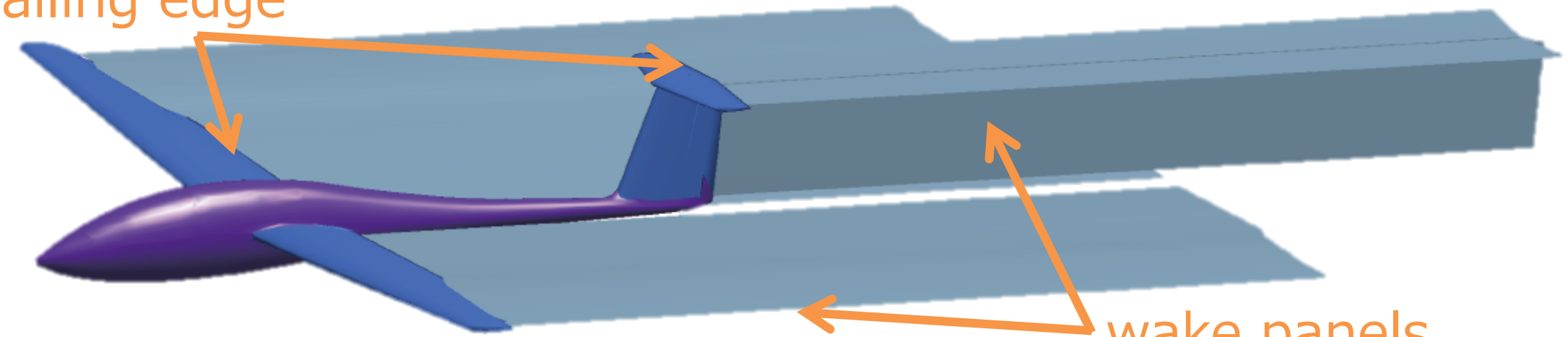


Wake Panel



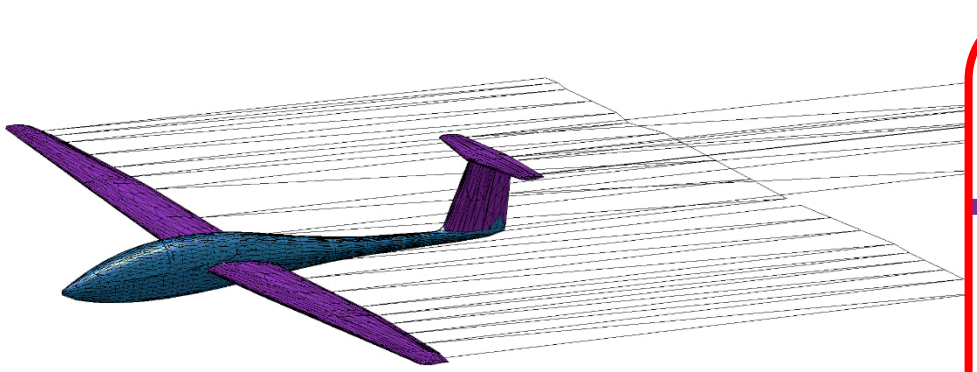
positive surface
trailing edge
negative surface

trailing edge

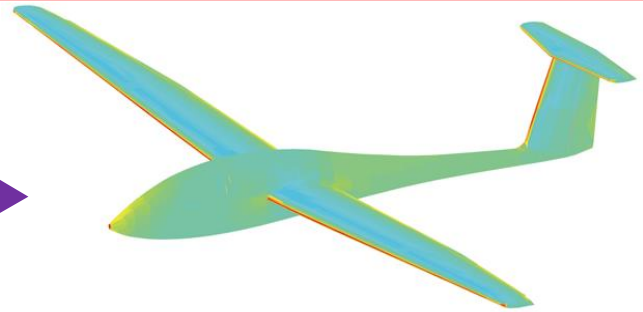


wake panels

Full Simulation Pipeline



Geometry Preprocessing

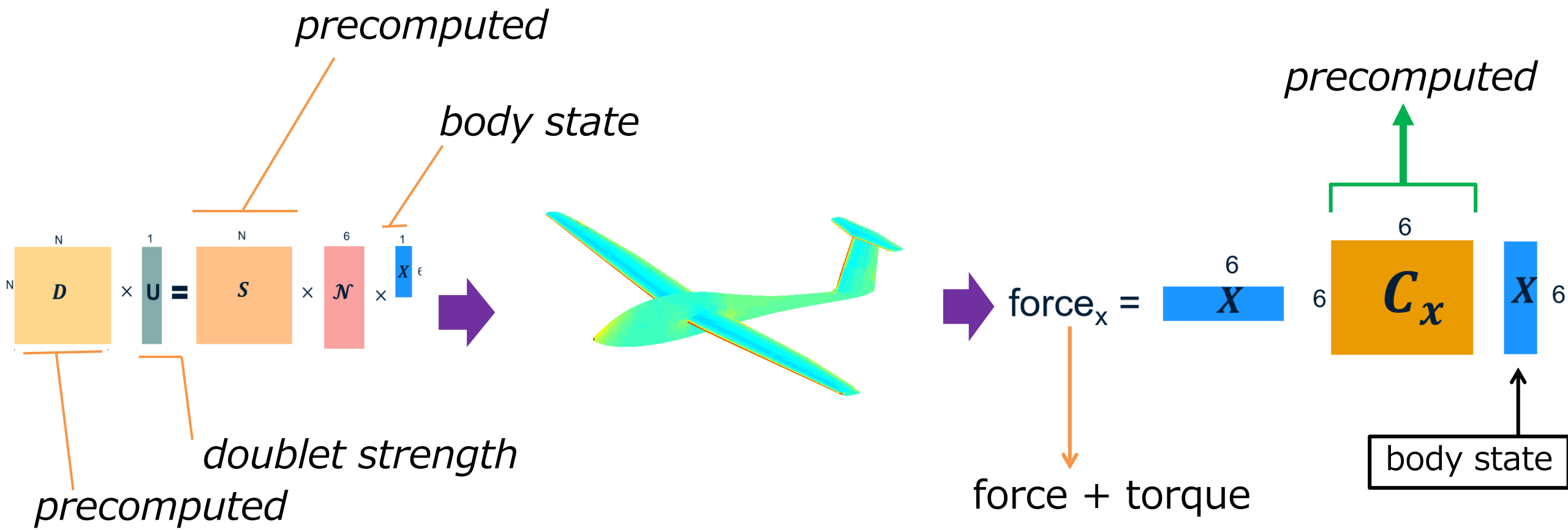


Aerodynamics Precomputation

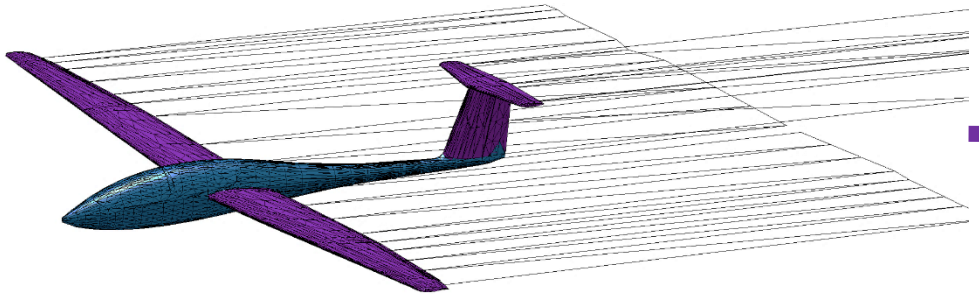
pre-computation

runtime

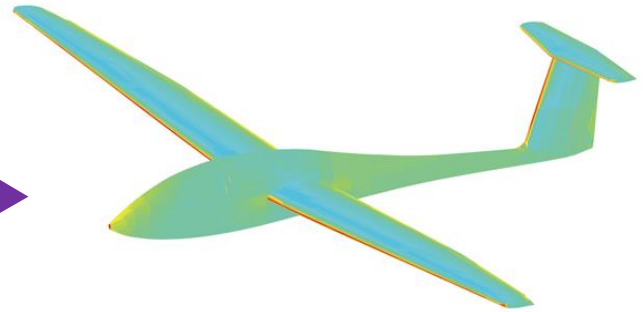
Aerodynamics Precomputation



Full Simulation Pipeline



Geometry Preprocessing



Aerodynamics Precomputation

pre-computation

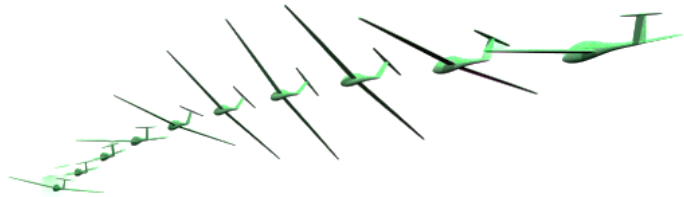
runtime

RIGD BODY Simulation

[Kobilarov et al, TOG2009]

Kinematic Equations:

$$\dot{R} = R\hat{\omega}, \quad \dot{b} = Rv$$



Dynamics Equations:

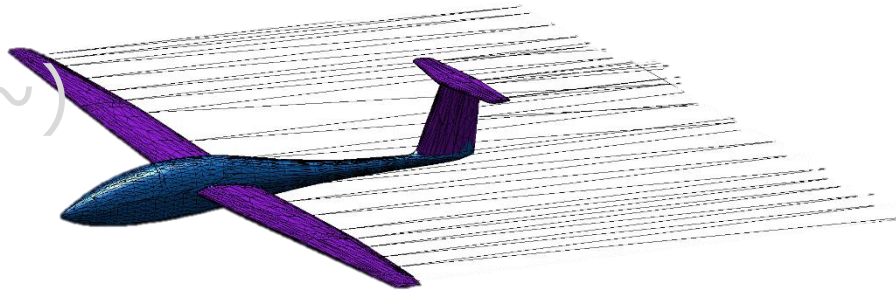
$$\begin{bmatrix} J\dot{\omega} \\ M\dot{v} \end{bmatrix} = \begin{bmatrix} J\omega \times \omega + Mv \times v \\ Mv \times \omega \end{bmatrix} + \begin{bmatrix} \tau \\ f + mR^T g \end{bmatrix}$$

Quadratic to body state!

Computational Framework

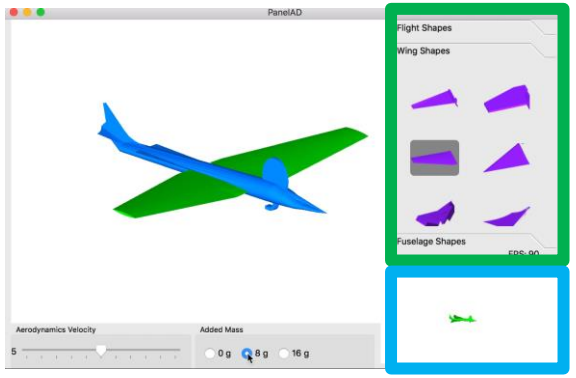
Aerodynamics Simulation Algorithm

- Precomputed panel method (x10,000~)
- Interactive simulation pipeline

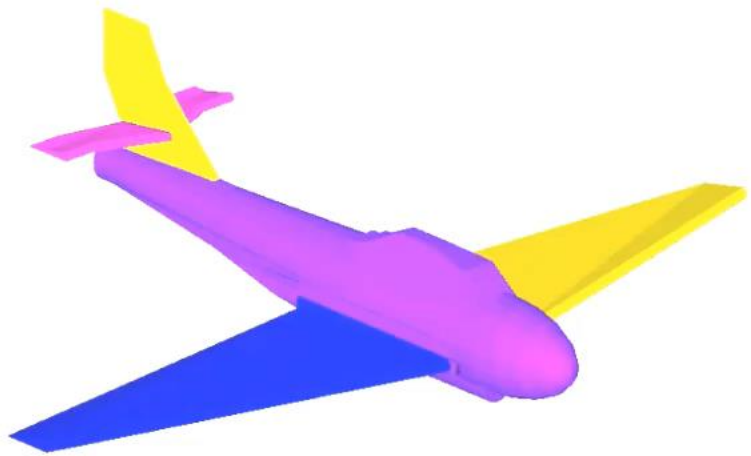


Interactive Glider Design System

- Assembly-based user interface
- Glider design and fabrication



Assembly-based modeling



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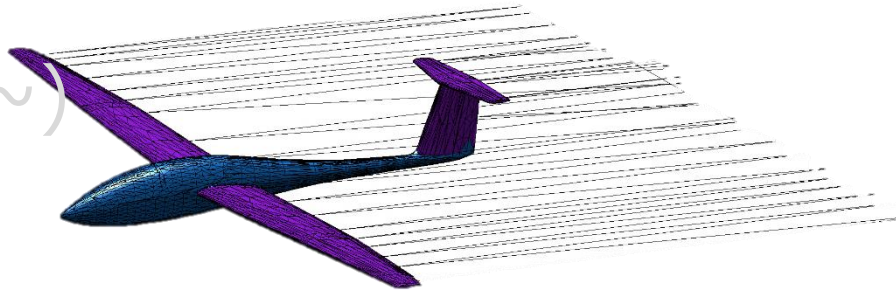

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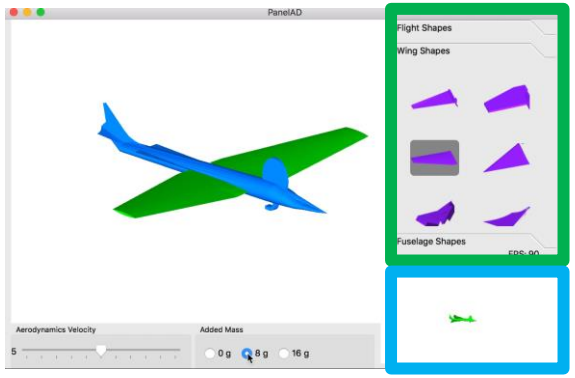
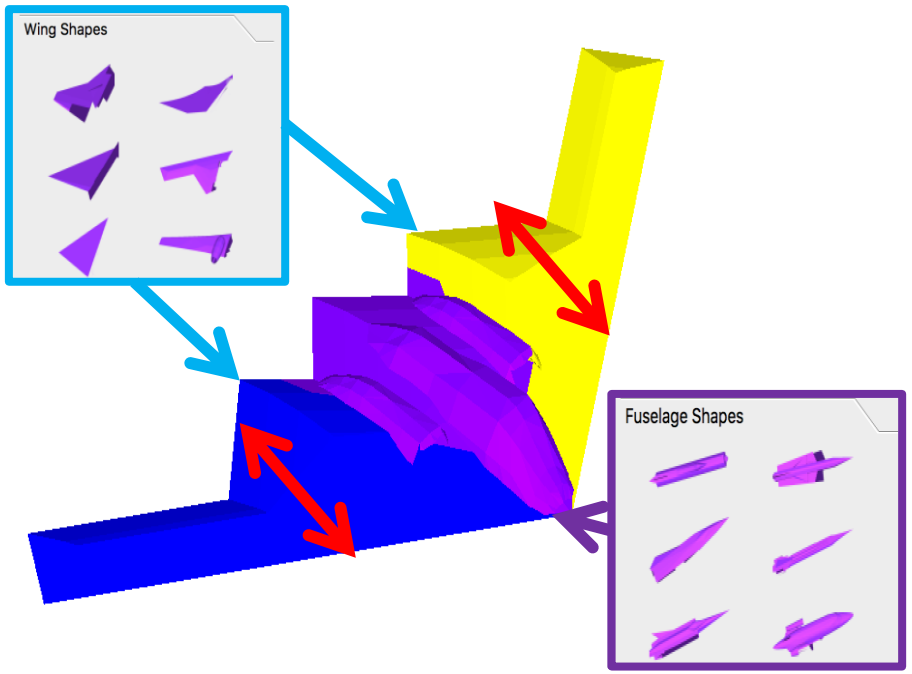


Glider Design



assembling&editing

rotation scaling translation

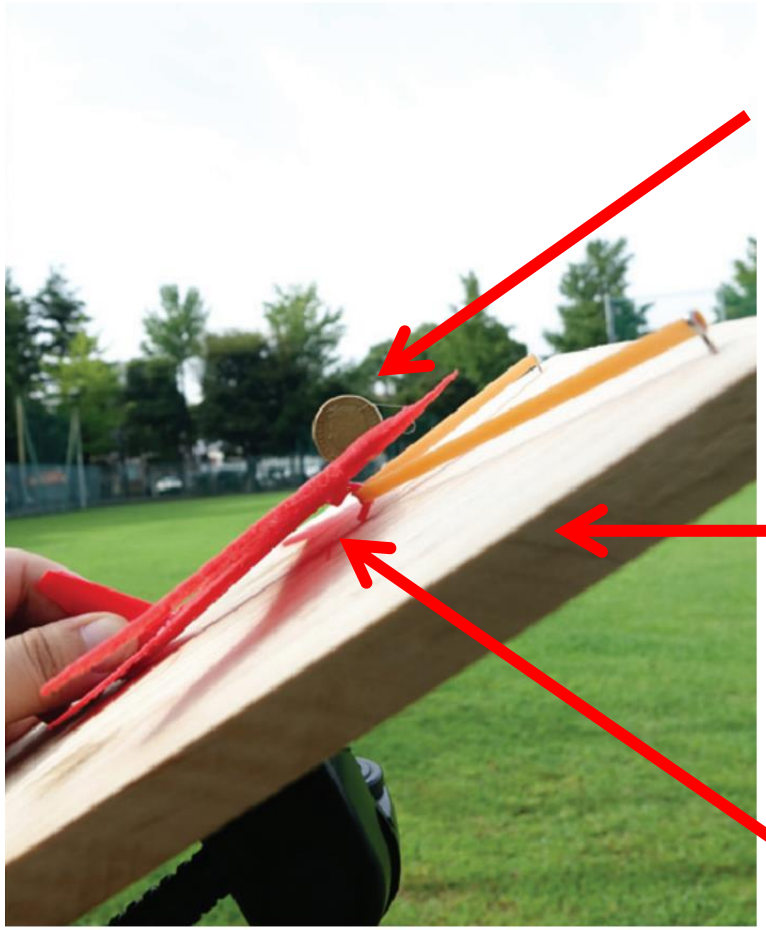
$$U = \left[P_1 R \;\; k P_2 R + P_1 \hat{T} \right] X$$

Doublet Matrix

Body State

Precomputed

Glider Fabrication



Fabricated Gliders


Insert a coin into the glider slot

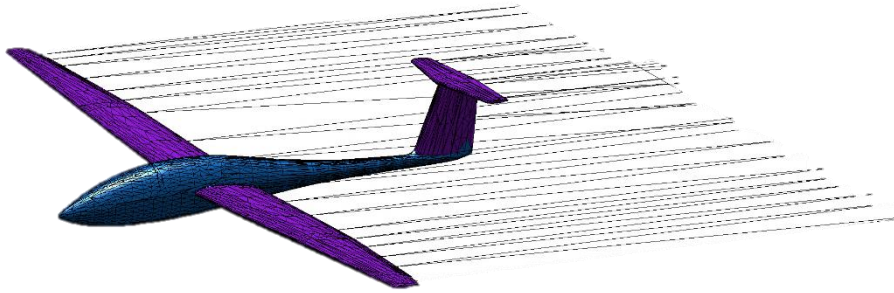
Results

Aerodynamics validation and glider design.

Results

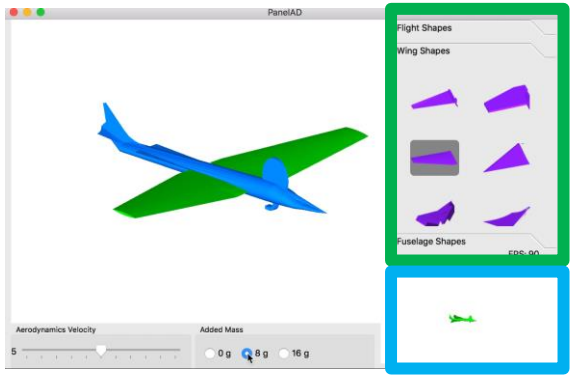
Aerodynamics Simulation Algorithm

- Aerodynamics validation
- Simulation comparison



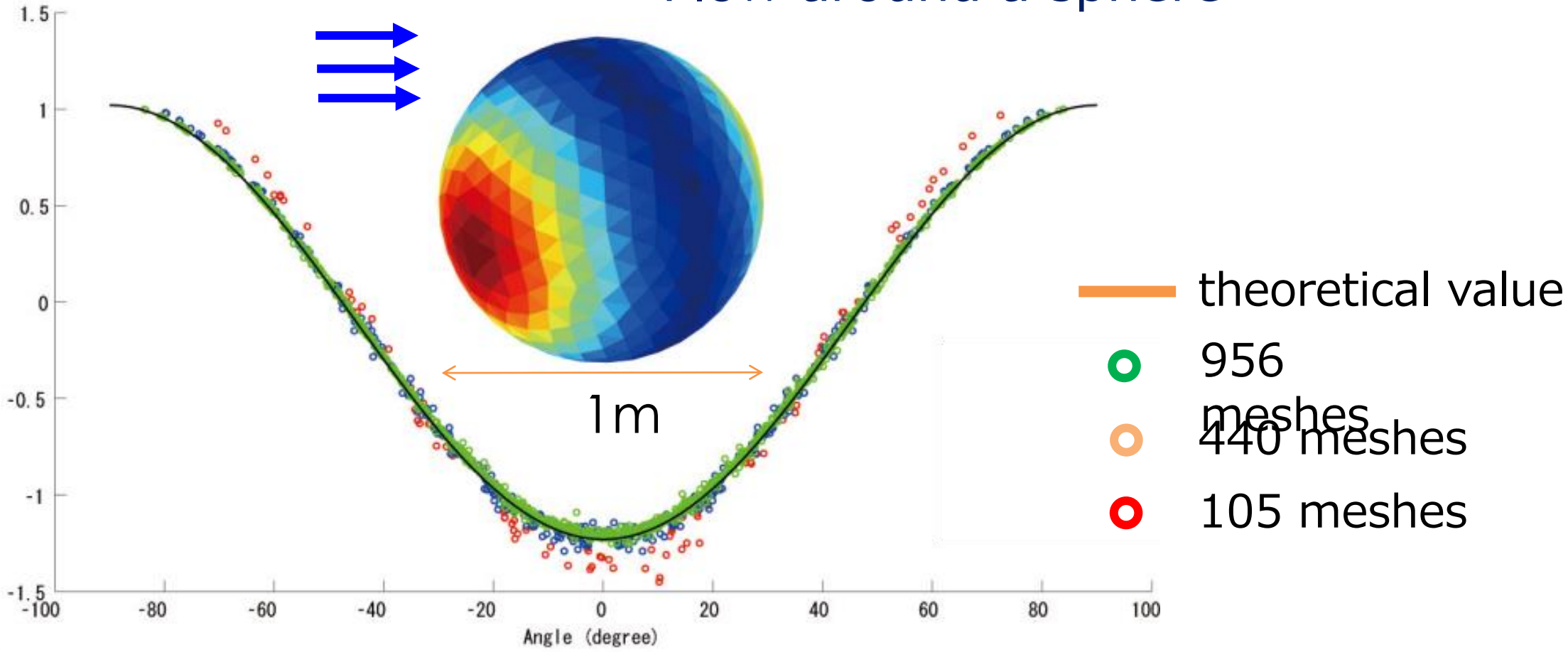
Interactive Glider Design System

- Glider design (stable & unstable)
- Bird glider design

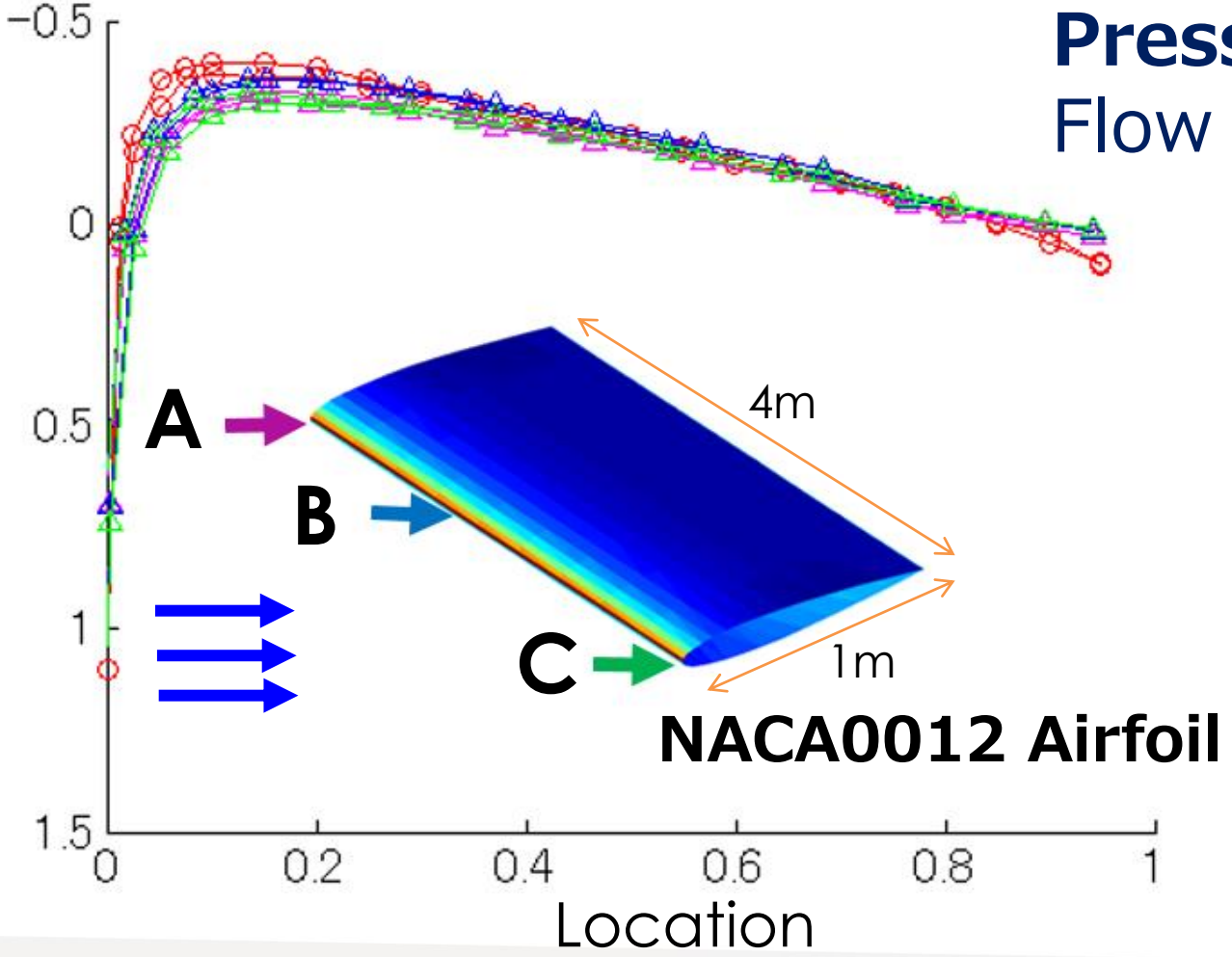


Validation: Sphere

Pressure Distribution:
Flow around a sphere



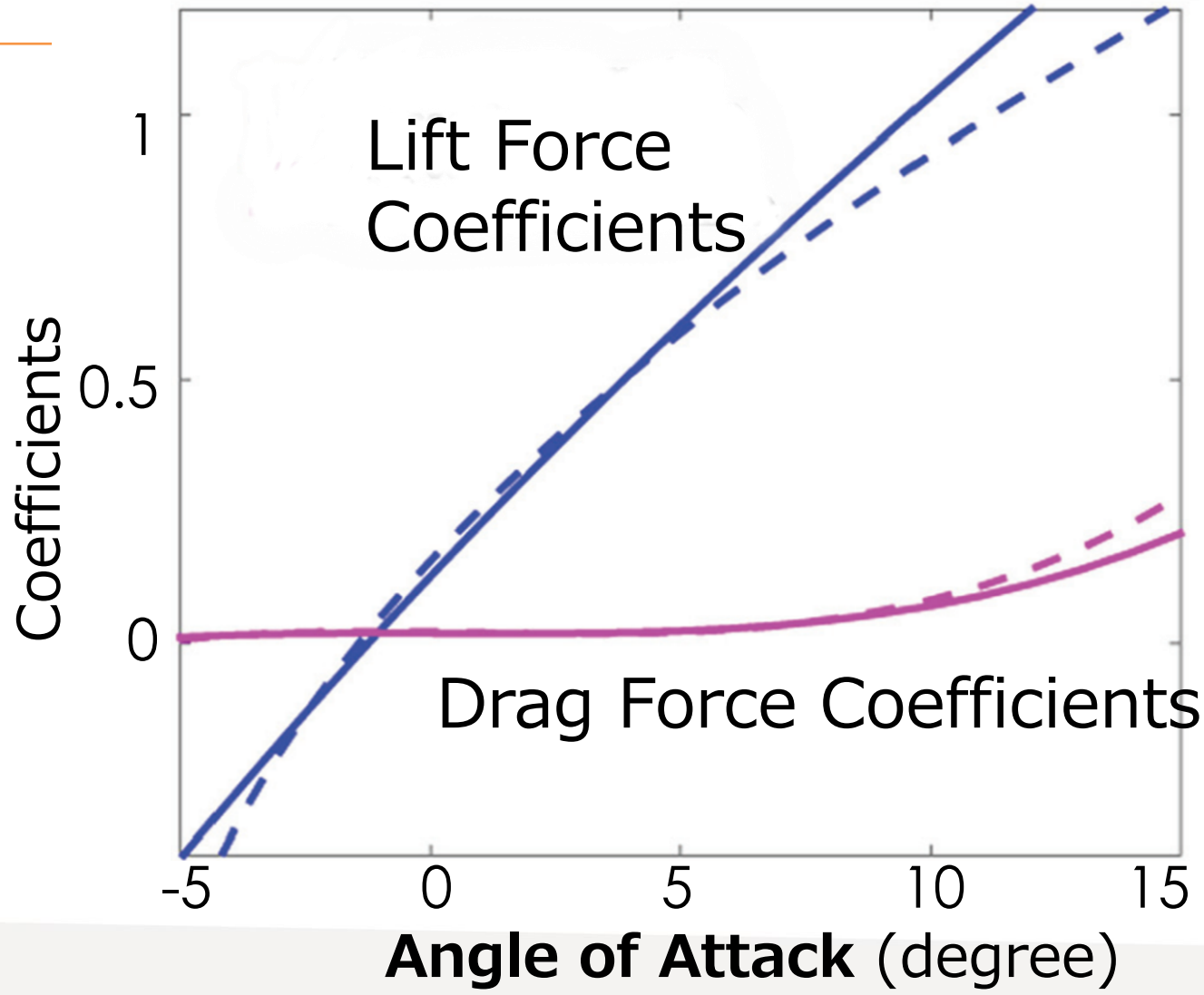
Validation: Airfoil



Pressure Distribution:
Flow around an airfoil

- wind tunnel data
- section A
- section B
- section C

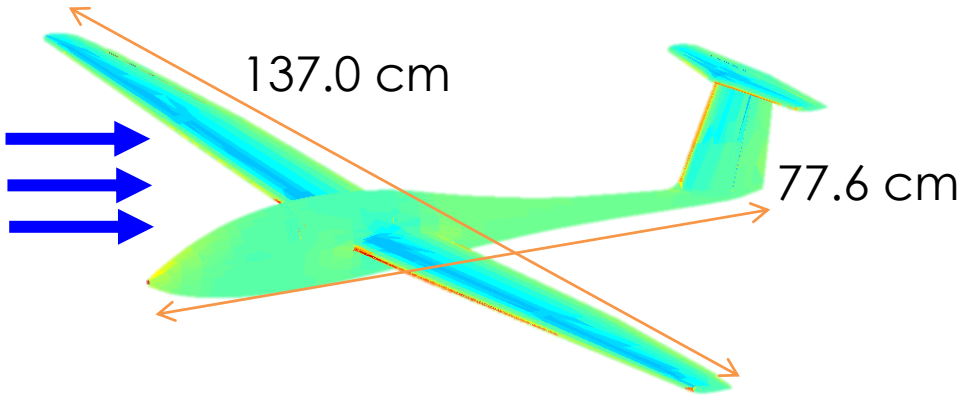
Validation: Glider



Pressure Distribution:
Flow around a glider

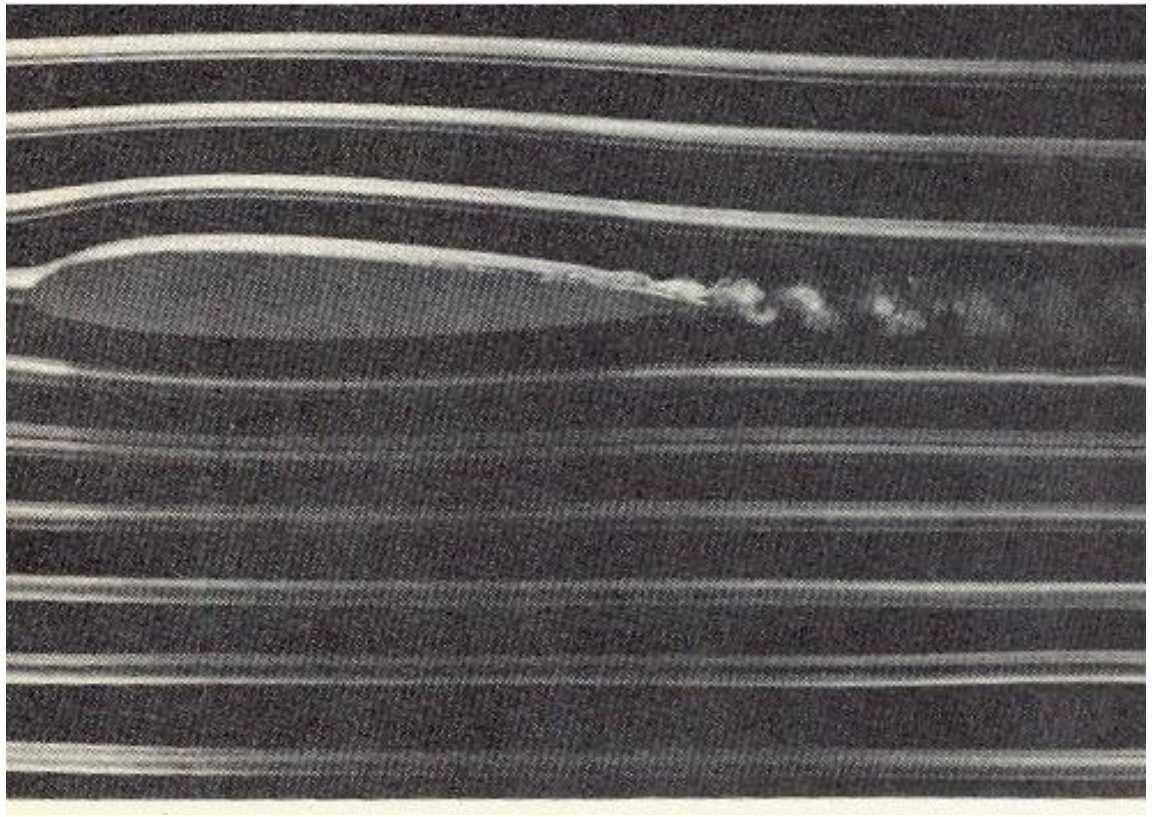
wind tunnel data

our model

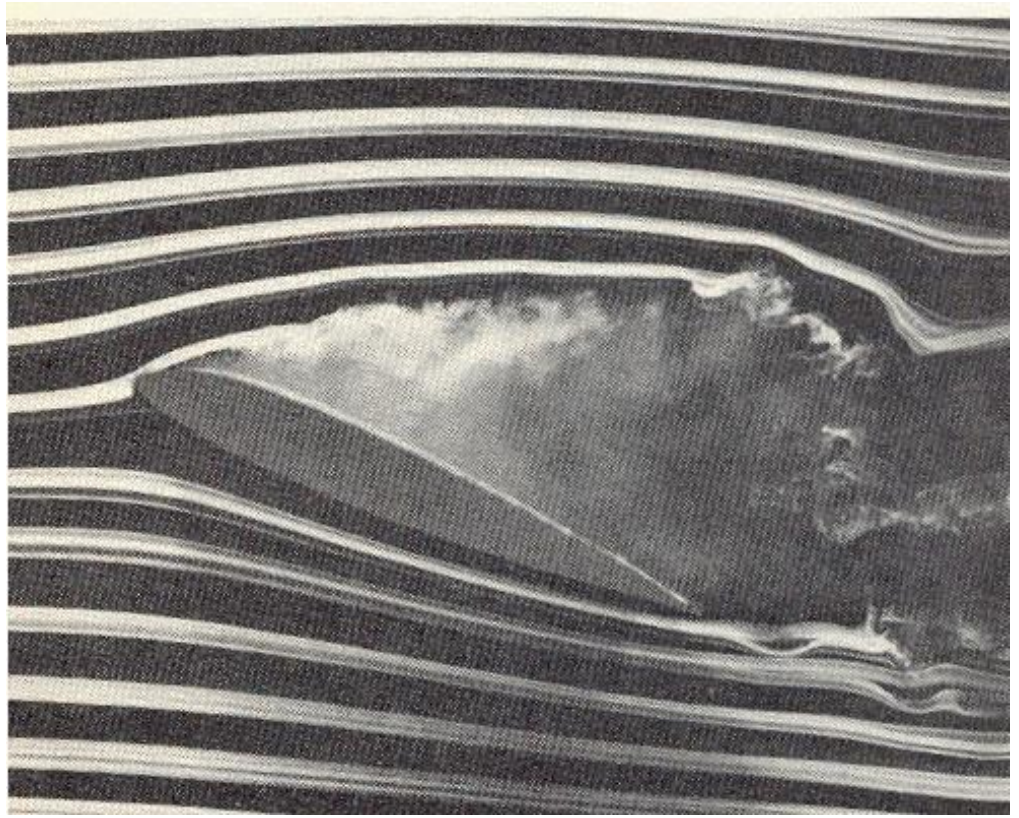


Influence of AoA

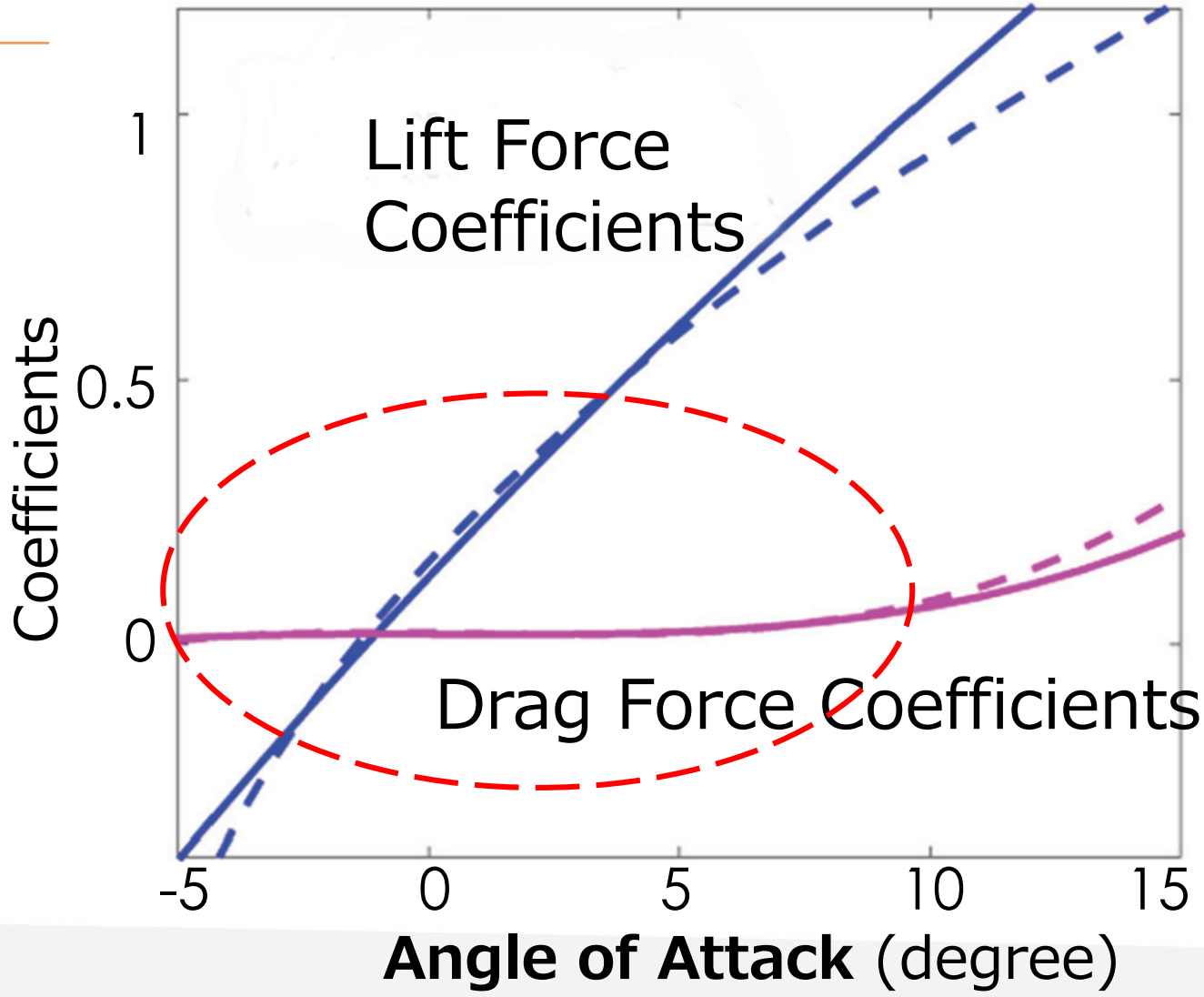
Wind Tunnel Visualization



Boundary layer separation @UAF Physics 211



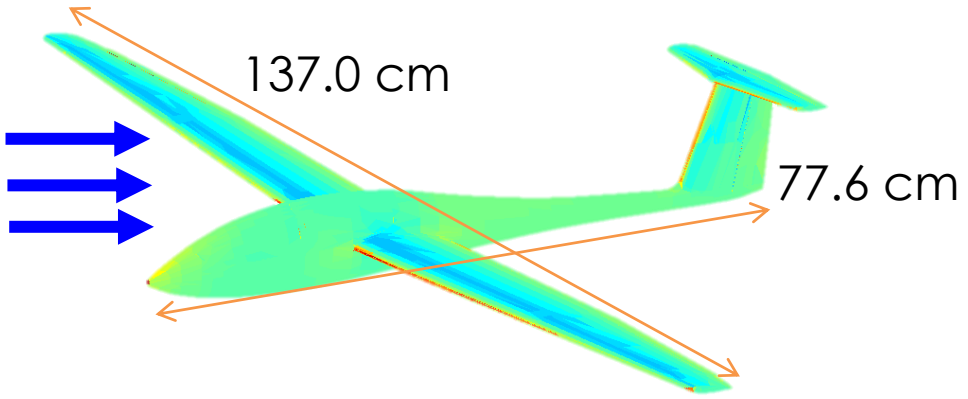
Validation: Glider



Pressure Distribution:
Flow around a glider

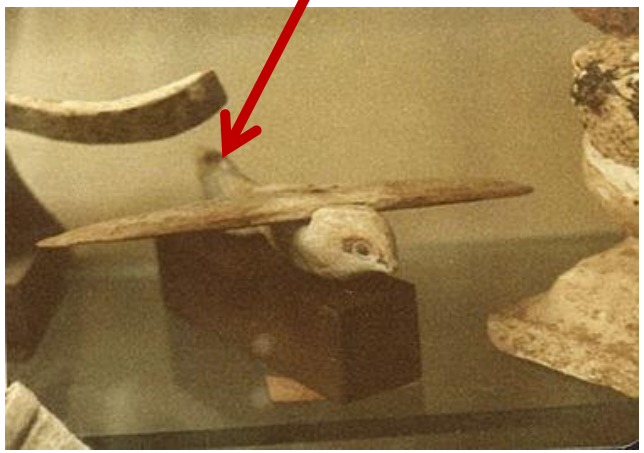
wind tunnel data

our model



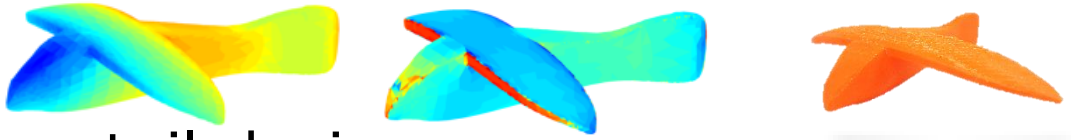
Validation: Comparison

Saqqara Bird: about 2,200 years old, excavated in 1898 from a tomb in Saqqara, Egypt.

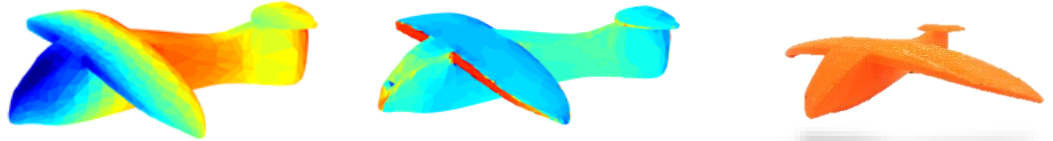


@wikipedia

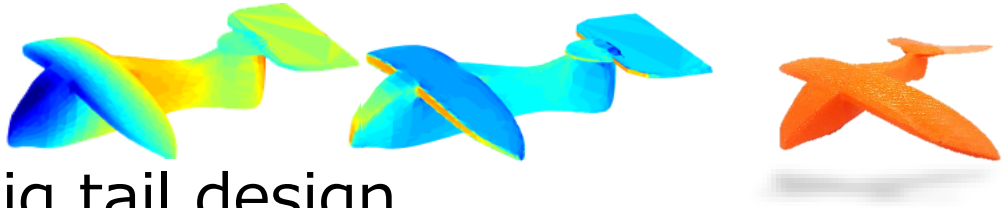
Source distribution | Pressure Distribution | Fabrication Results



no tail design — not stable, tumbling a lot



small tail design — not stable, tumbling few



big tail design — stable, no tumbling

FPS: 152.67

Gliding simulation

No tail design:

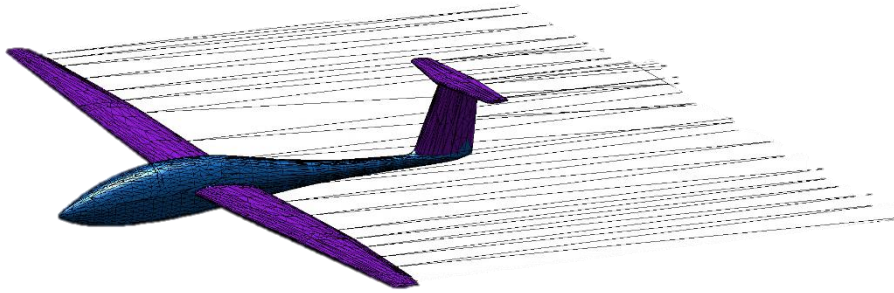
not stable

tumbling a lot

Results

Aerodynamics Simulation Algorithm

- Aerodynamics validation
- Simulation comparison



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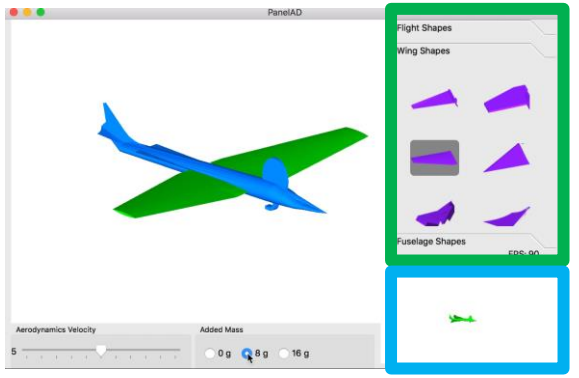
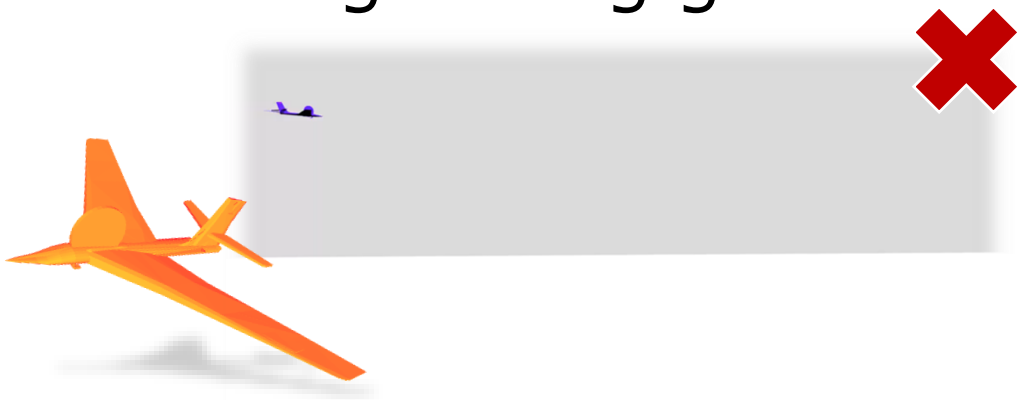
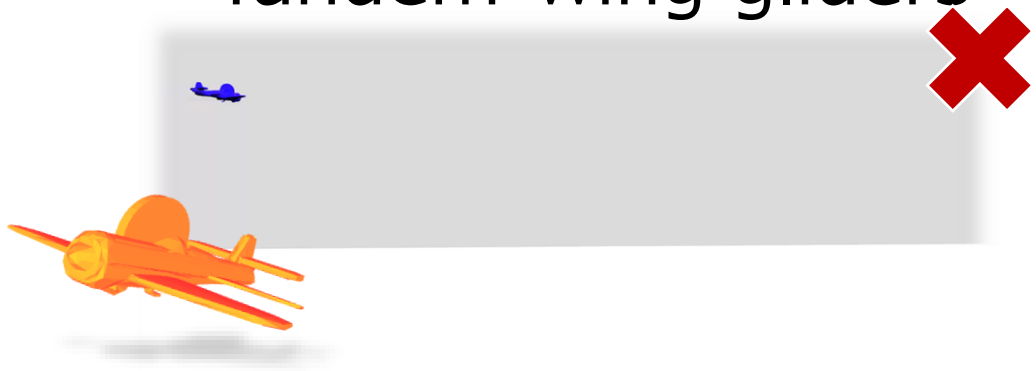


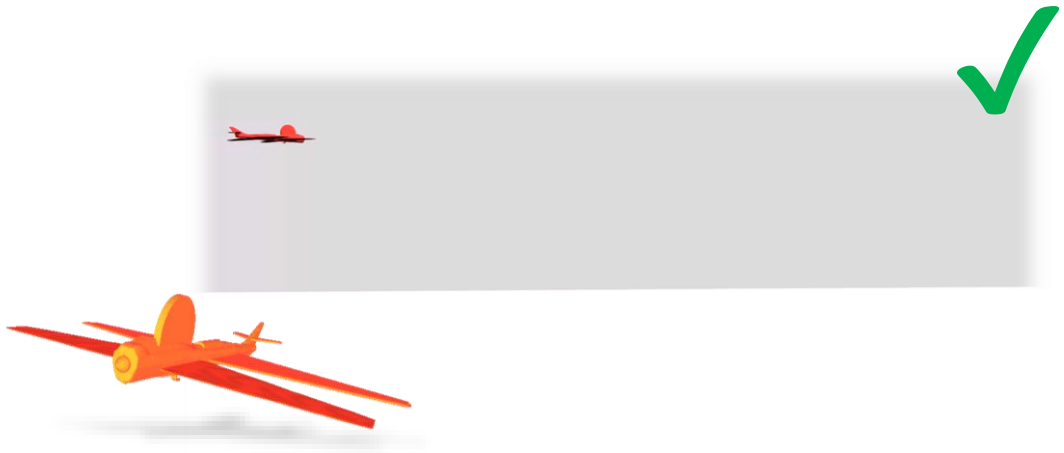
Glider Design

Single-wing gliders



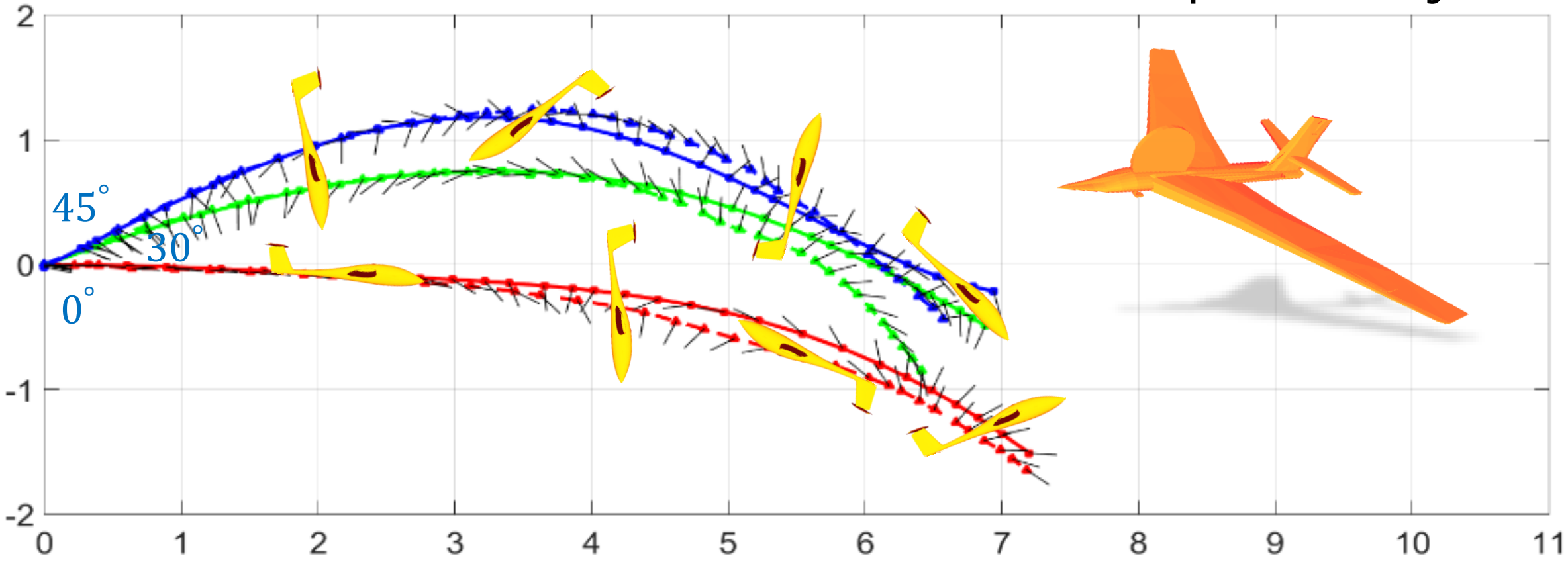
Tandem-wing gliders





Glider Design **unstable**

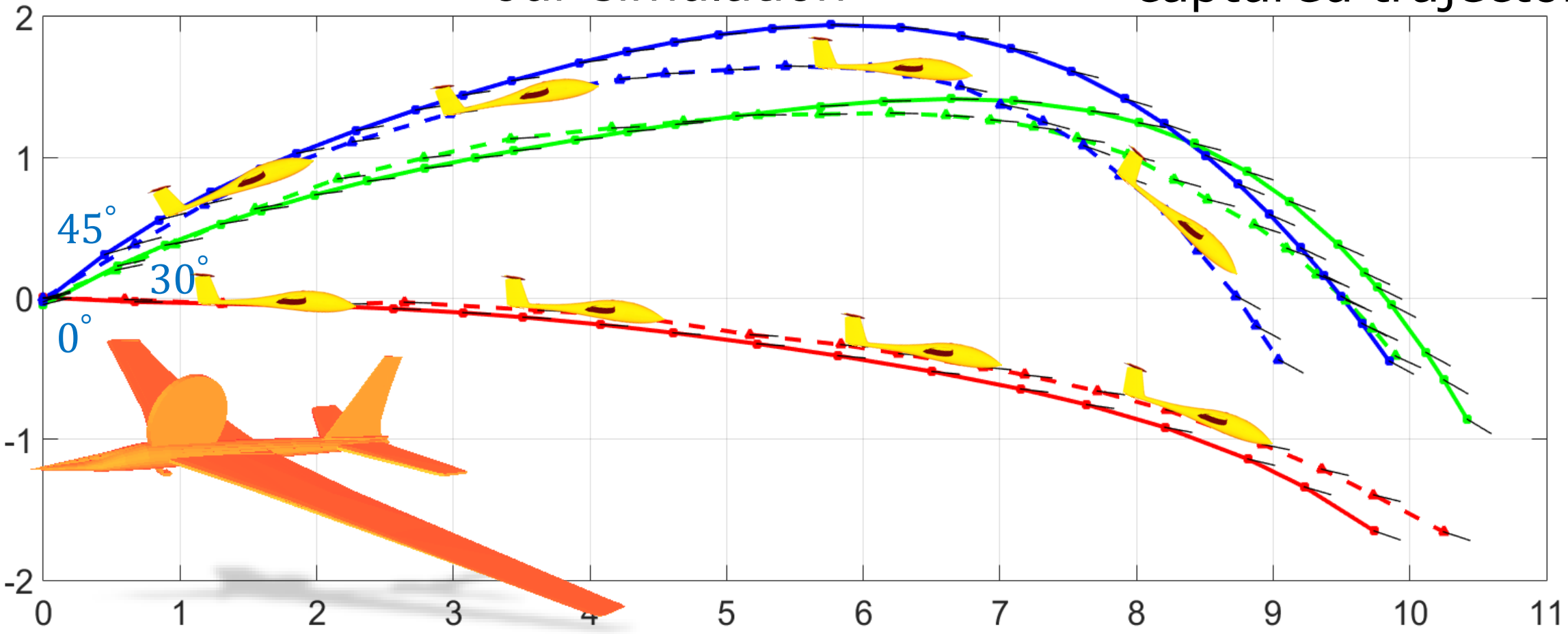
our simulation captured trajectory




Launch Angle: 0°
unstable

Glider Design **stable**

our simulation captured trajectory

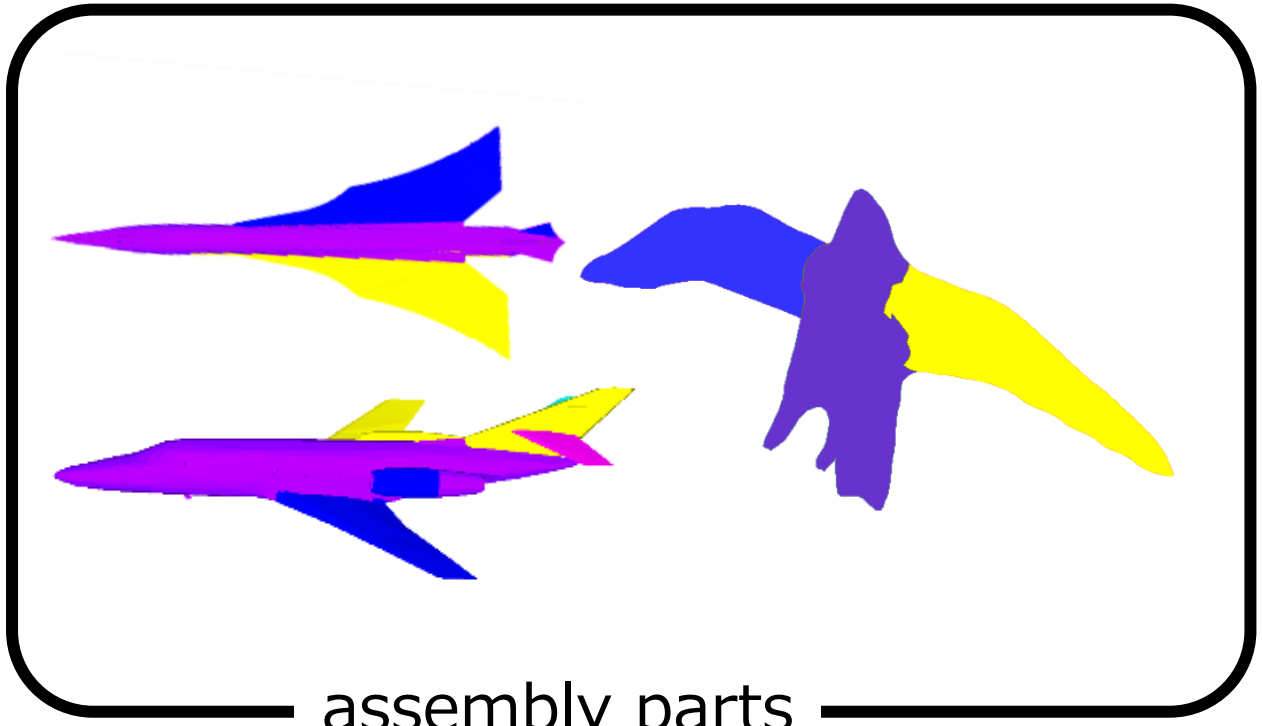



Launch Angle: 0°
stable


Back view

Bird Glider

A normal glider fuselage with bird wings

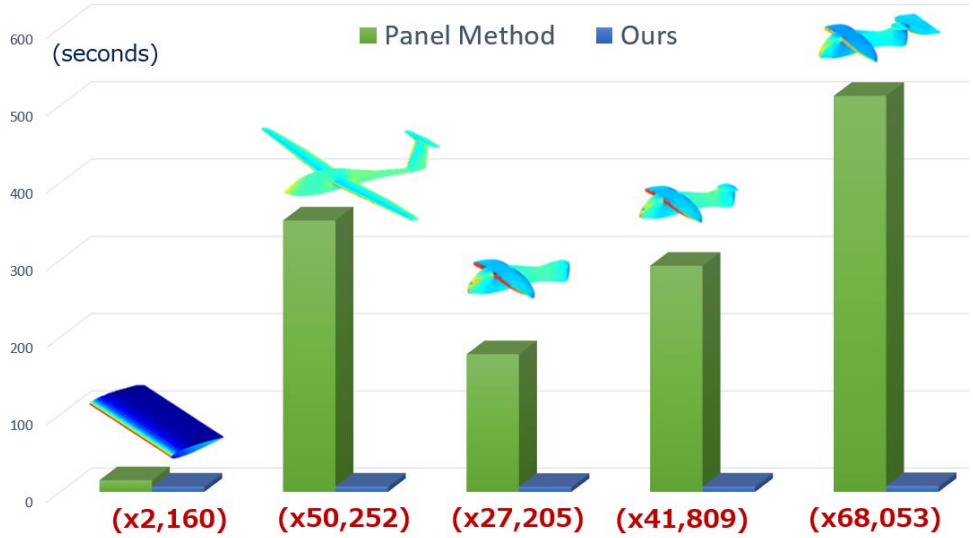


assembly parts

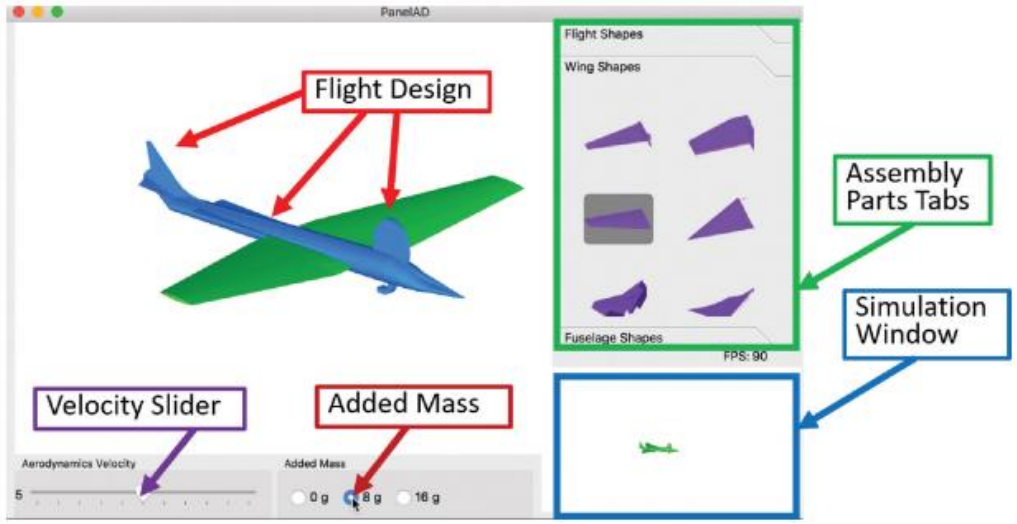

Back view

Conclusion

Precomputed Panel Solver

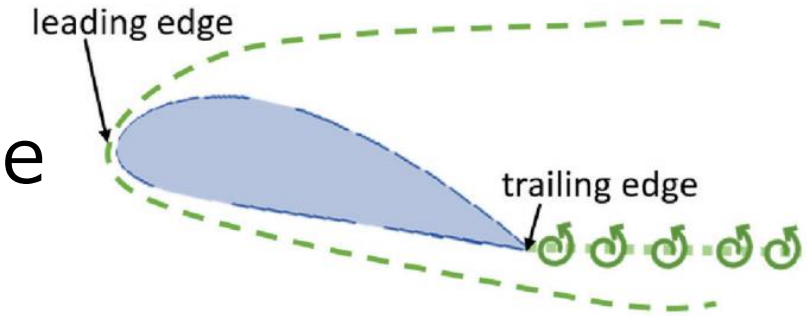


Interactive Glider Design

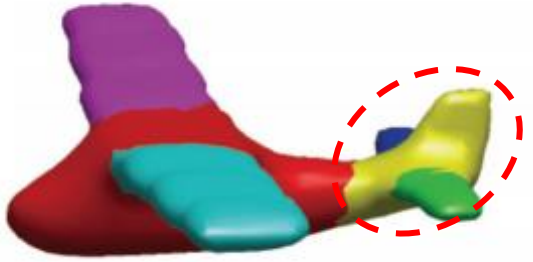


Limitations

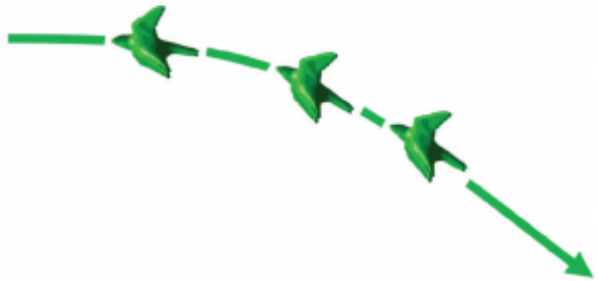
We assume potential flow, so cannot handle unstable turbulences



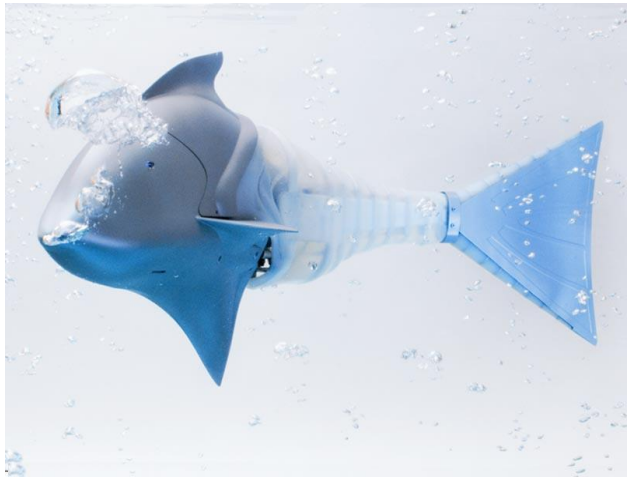
Mesh segmentation can be wrong, leading to inaccurate simulation.



We assume forward flight. It cannot handle flying in other directions.



Future Work



FESTO

Thank You!
Q&A