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DEPARTMENT OF AERONAUTICAL ENGINEERING

CHAIR OF FLIGHT VEHICLE DYNAMICS

Flapping wing vehicle for Mars exploration

Research Project - financed by Croatian Scientific Foundation (IP-2016-06-6696)

NUMECA4EMBEDDED

'Numerically efficient computational algorithms for embedded multi-physical systems in vector spaces and manifolds'

Partner institutions:

- *Technische Universität München (TUM), Germany*
- *Institute for Mechanical Systems, ETH, Zürich*
- *Politecnico di Milano (POLIMI), Italy*
- *Institute of Mathematics, Martin Luther University, Germany*
- *Robotics Institute, School of Mechanical Engineering and Automation, Beijing University of Aeronautics and Astronautics, China*
- *Institute of Robotics Austria, Johannes Kepler University, Austria*
- *Faculty of Science, Department of Mathematics, University of Zagreb, Croatia*
- *Department of Continuum Mechanics and Structures, UPM, Madrid*

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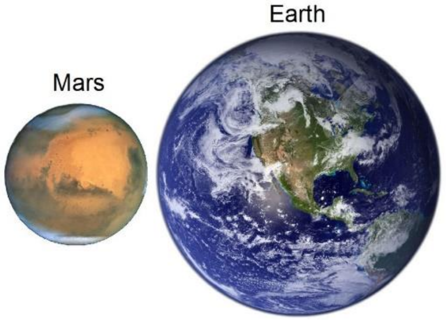
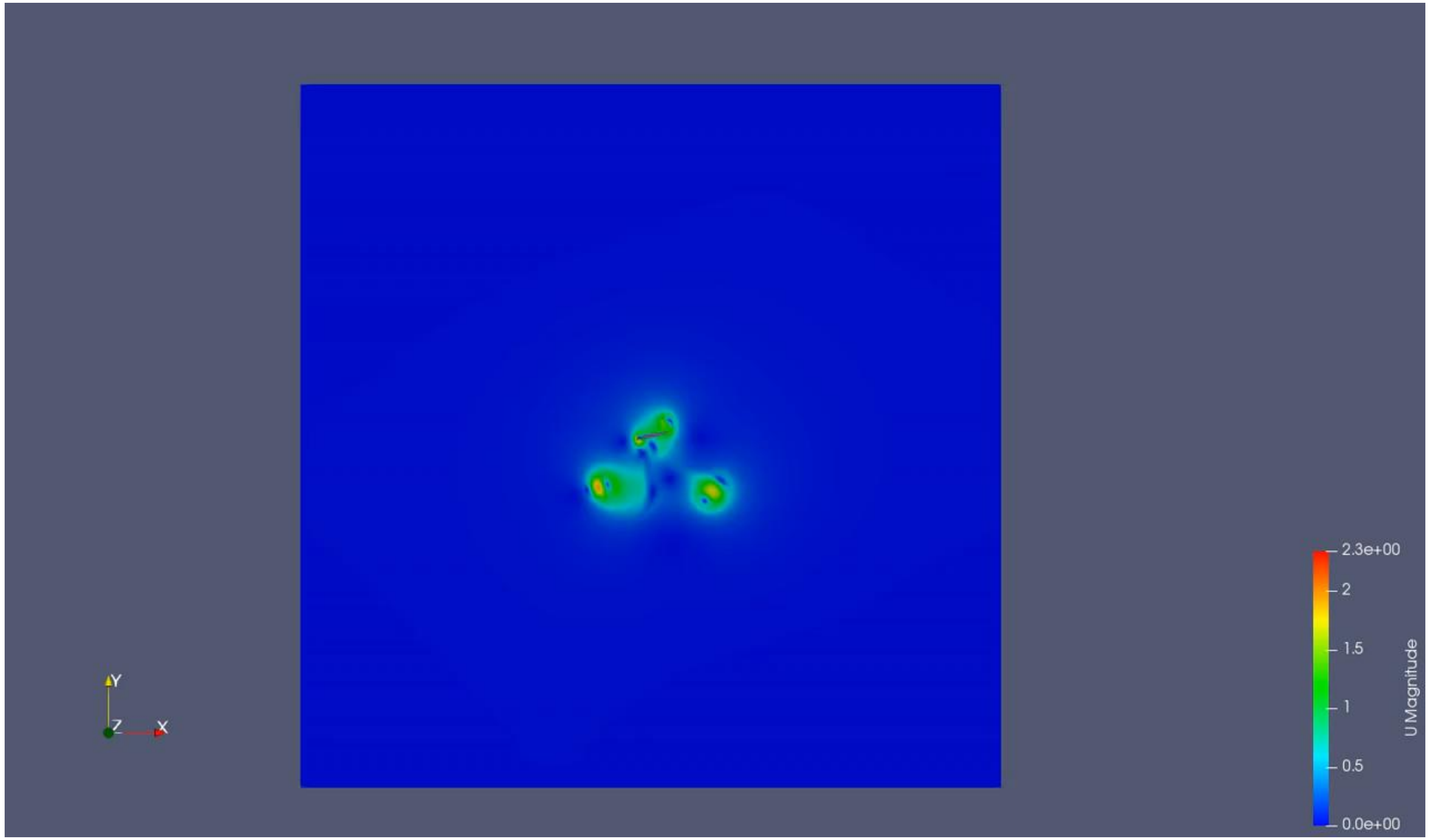
- Low atmospheric density on Mars (air density is 1.3% of that on Earth and gravitational acceleration is 38% of Earth’s) → low Reynolds number
  - Conventional aircraft designs have limitation
    - fixed wing vehicles must fly fast to avoid stall (>350 kmph) → passing over regions too quickly, cannot successfully land on uneven terrain for the mission stop or to refuel; ‘hard landings’
    - rotary wing vehicles allow for take-off and landing / but rotor tips rapidly exceed the Martian lower speed of sound → rotational speeds insufficient to lift; difficult to manoeuvre
  - Why flapping wings?
    - high lift generating capability at low Reynolds number → allow to fly slow, manoeuvre easily and perform vertical take-off and landing
    - reciprocating nature of flapping wings → resonant operation → energy efficiency; harvesting energy from the ambiental flow
    - should better sustain collisions with hard environment → more robust operation; mission planning activities enhanced



Numerical example: Butterfly wing



- **Velocity field distribution for butterfly wing model**

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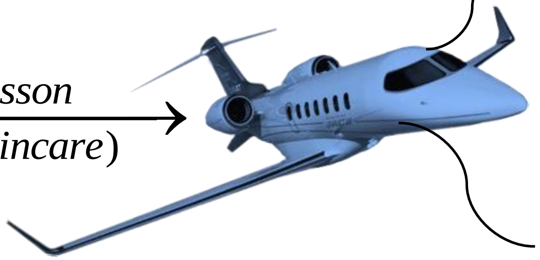
Fluid - Flying vehicle / ‘hybrid’ modelling:

- differential-geometric reductions (Lie groups) + numerical discretisation (BEM)

- **Rigid vehicle**

$$G = \mathbf{R} \in SO(3)$$

$$SO(3) \xrightarrow[(Euler-Poincare)]{Lie-Poisson}$$



$$L(\mathbf{R}, \dot{\mathbf{R}}) = tr((\mathbf{R}^{-1}\dot{\mathbf{R}})^T\, I\, \mathbf{R}^{-1}\dot{\mathbf{R}}) \rightarrow \frac{1}{2}\omega^T I \omega$$

ω

- Euler equations

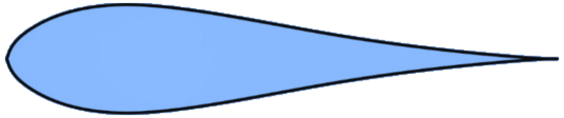
  in Lie-Poisson form:

$$\dot{y} = -\omega \times y, \quad y = I\omega \in so(3)^* \quad (\, I\dot{\omega} = I\omega \times \omega \,)$$

$$(no\ \mathbf{R}\ !!)$$

- **Rigid vehicle + fluid (planar case)**

$$SE(2) \xrightarrow[(left)]{Poisson}$$



$$\xleftarrow[(right)]{Symplectic\ (\Gamma)} \mathrm{Diff}_{\mathrm{Vol}}(\mathscr{F})$$

$$T^*SE(2) \rightarrow se^*(2)$$

$$(no\ "translations"\ !!)$$

$$\dot{\Pi} = (\mathbf{P} \times \mathbf{v}) \cdot \mathbf{b}_3$$

$$\dot{\mathbf{P}} = \mathbf{P} \times \omega + \Gamma \mathbf{b}_3 \times \mathbf{v}$$

$$\mathbf{P}, \Pi \in se^*(2)$$

$$T^*Q \rightarrow T^*SE(2)$$

$$(no\ fluid\ variables\,!!)$$

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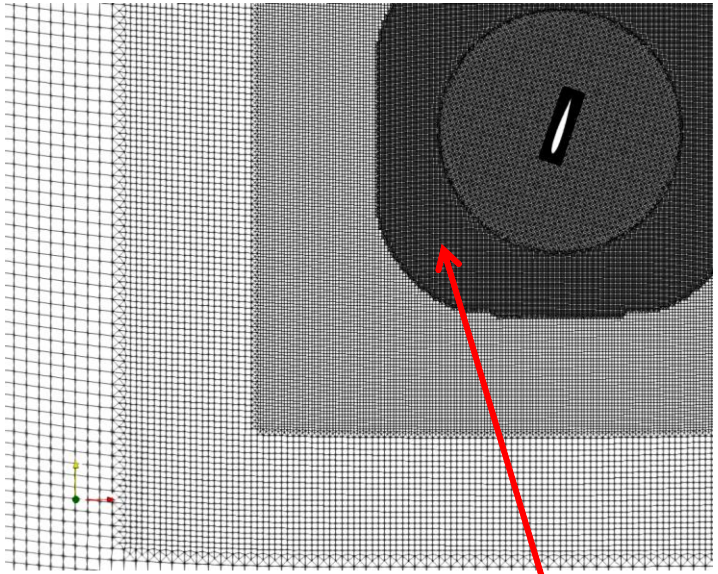
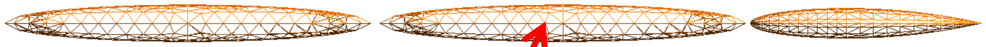
Fluid volume discretization -> Boundary surface discretization

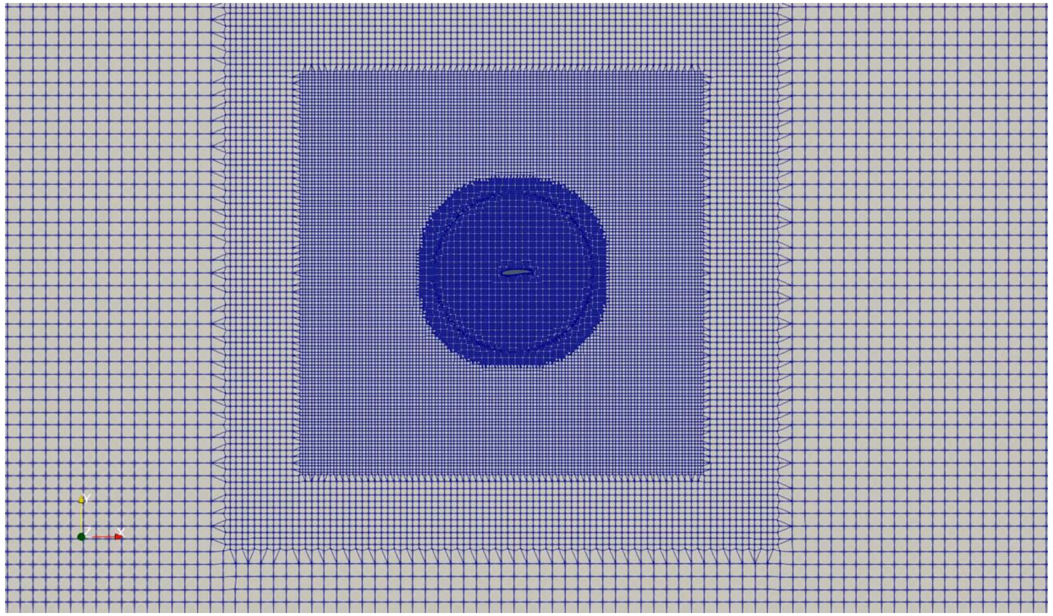
- **Multiple orders of magnitude fewer variables**

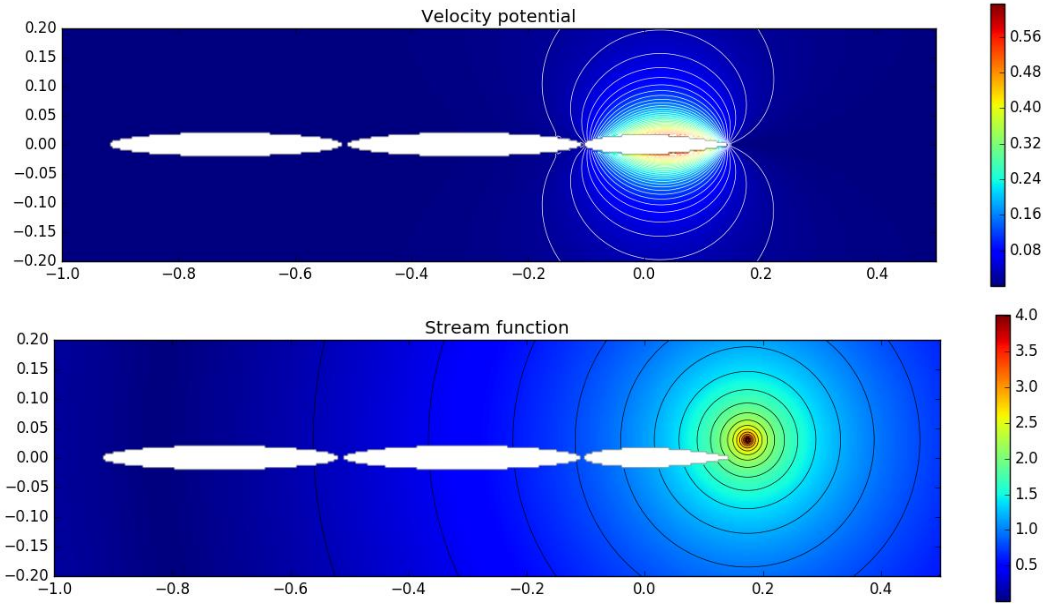




$$T_{\mathcal{F}} = \frac{1}{2}\rho_{\mathcal{F}} \int_{\mathcal{F}} \mathrm{div}\left(\phi \nabla \phi\right) dV = -\frac{1}{2}\rho_{\mathcal{F}} \int_{\partial \mathcal{B}} \phi \nabla \phi \cdot \mathbf{n}\, db$$

Finite volume method -> Boundary element method





- Problems with mesh deformations
- Stability/convergence problems
- Calculating large fluid domain
- Computational time measured in days

- Calculating only effects of the fluid on the body
- Computational time measured in minutes
- Can be used in optimal control/design loop

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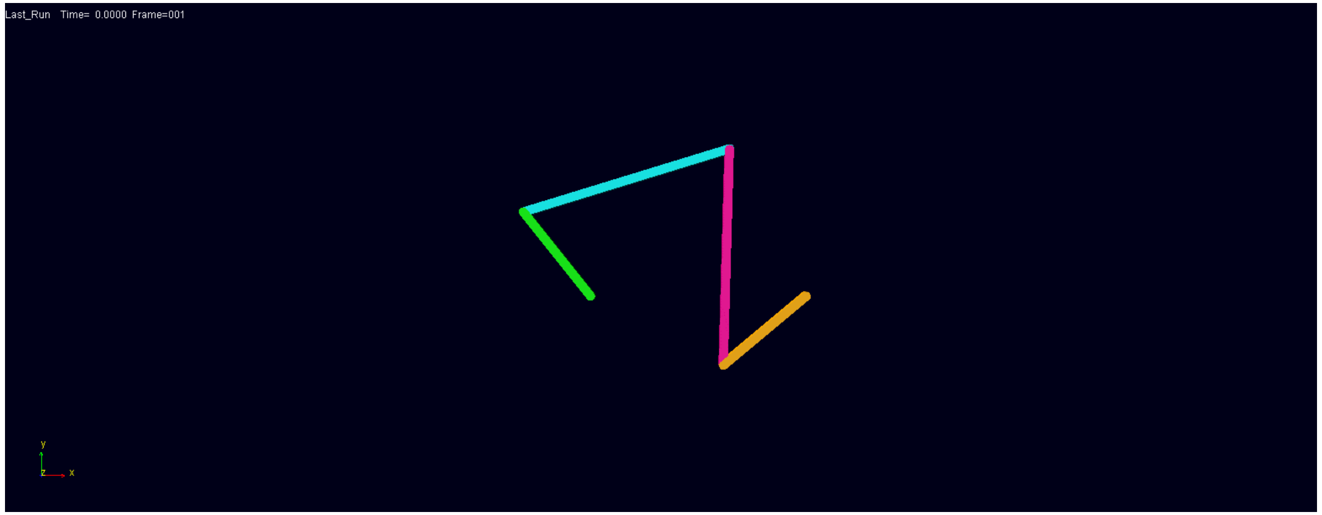
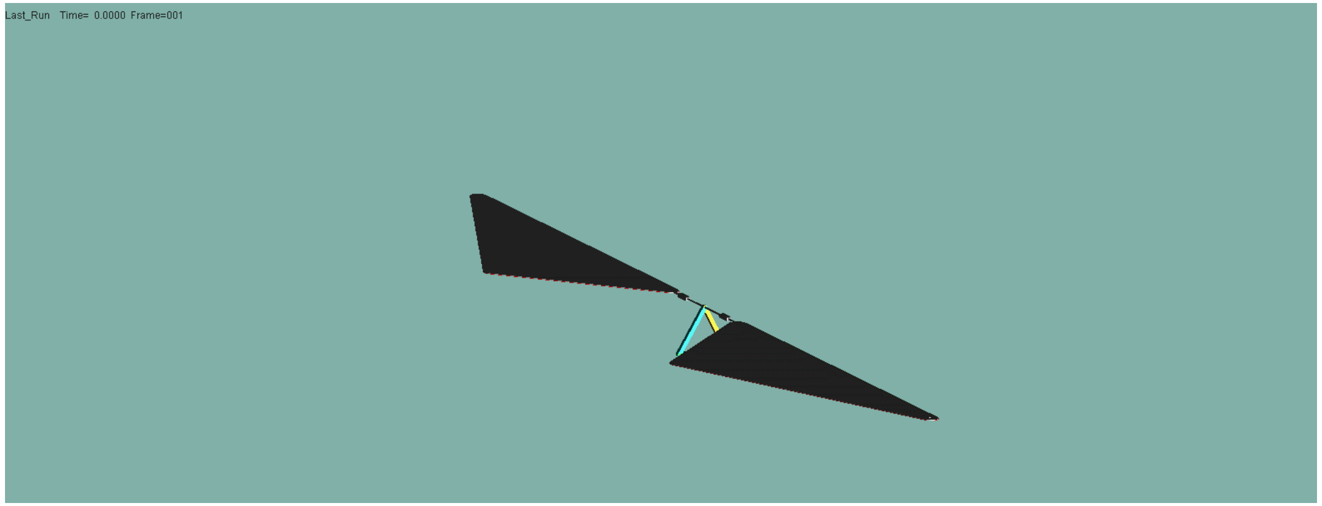
Variations of wing mechanism….(initial study)





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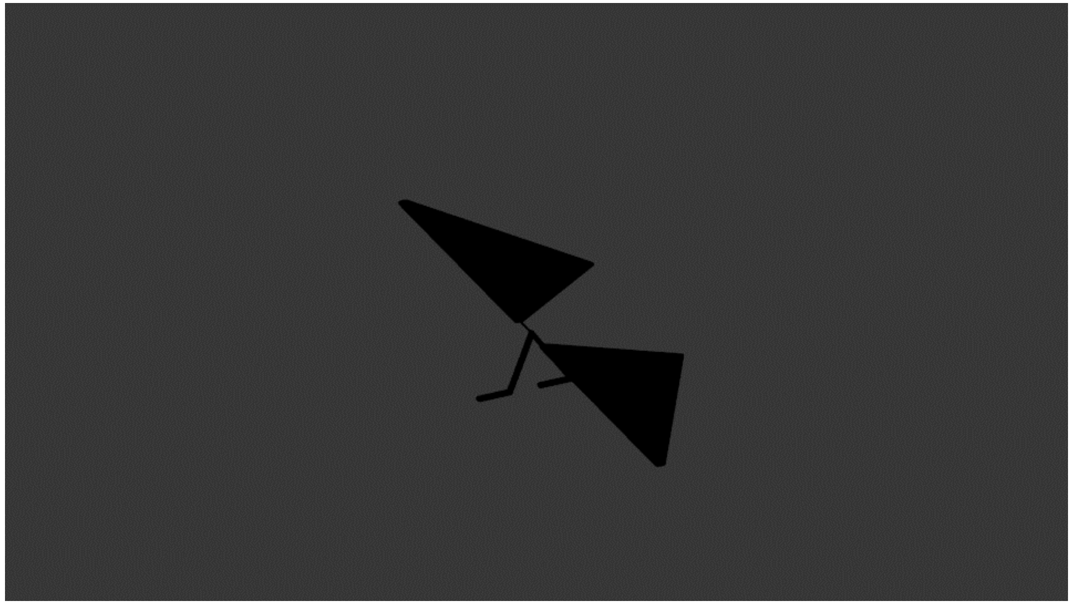
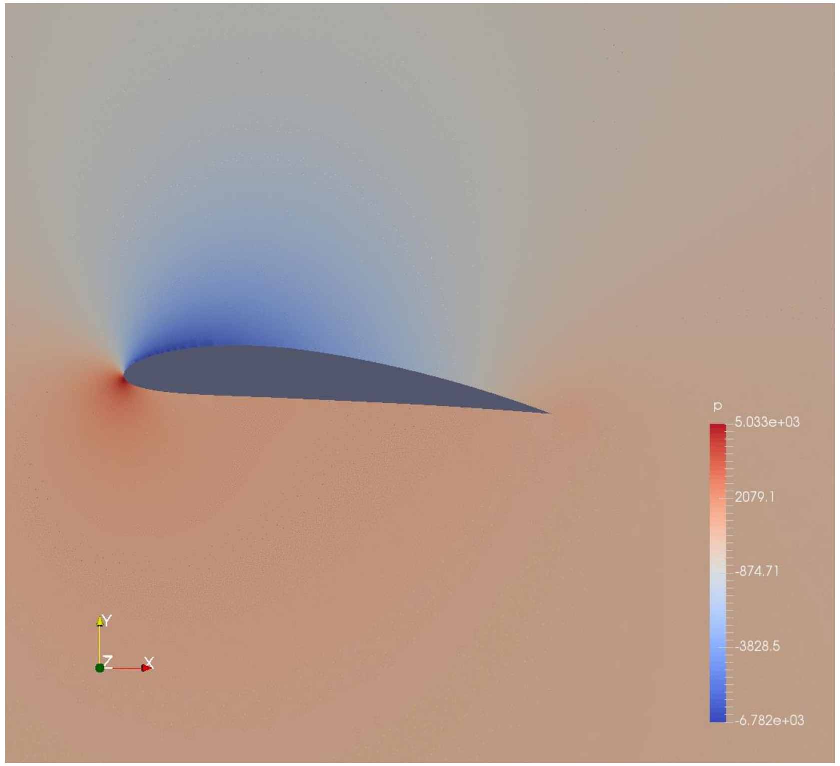
Dynamic coupling with fluid flow

- MBDyn, OpenFOAM (open source)





Experiments …/collaboration with:

- Beijing University of Aeronautics and Astronautics (BUAA)
- Harbin Institute of Technology …. / Mars chamber

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- **Thank you for your ATTENTION**