



# 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*

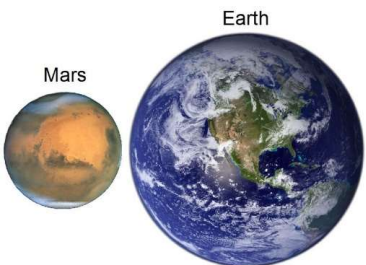
- **Low atmospheric density on Mars (air density is 1.3% of that on Earth and gravitational acceleration is 38% of Earth's) → low Reynolds number**

➤ **Conventional aircraft designs have limitation**

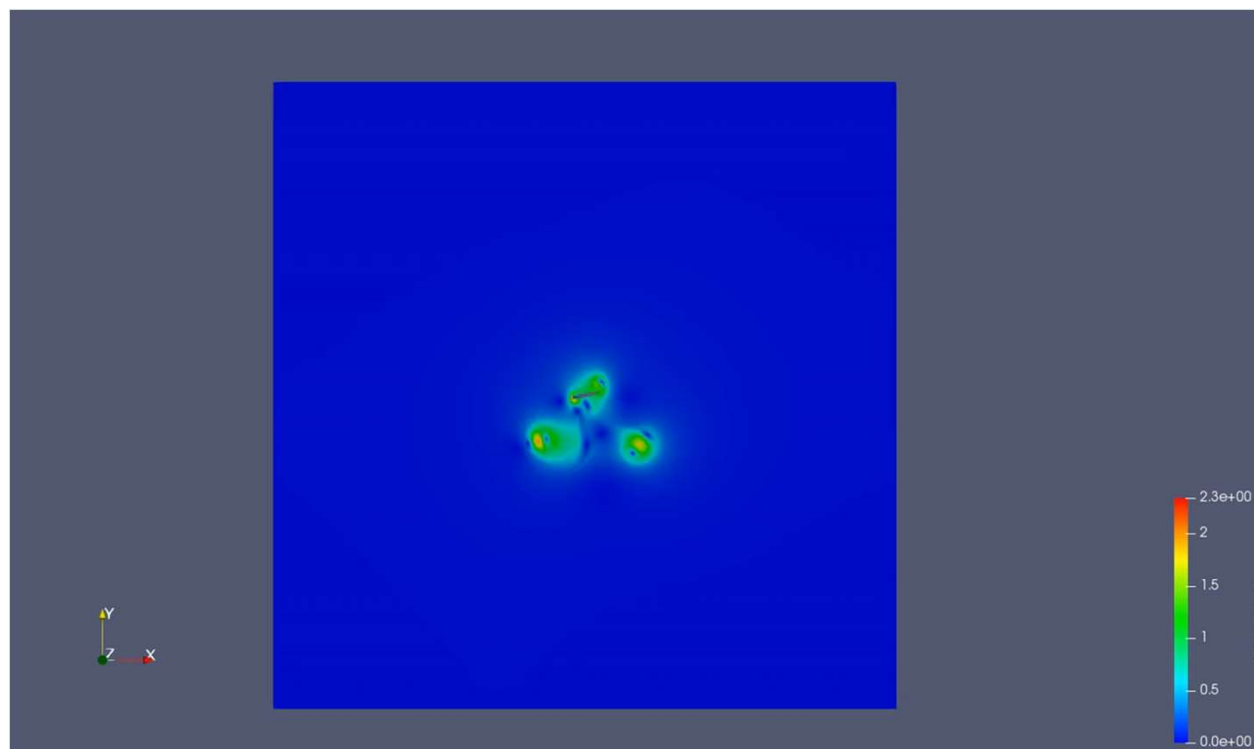
- fixed wing vehicles must fly fast to avoid stall (>350 kmph) → passing over regions too quickly, cannot successfully land on uneven terrain for the mission stop or to refuel; 'hard landings'
- rotary wing vehicles allow for take-off and landing / but rotor tips rapidly exceed the Martian lower speed 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

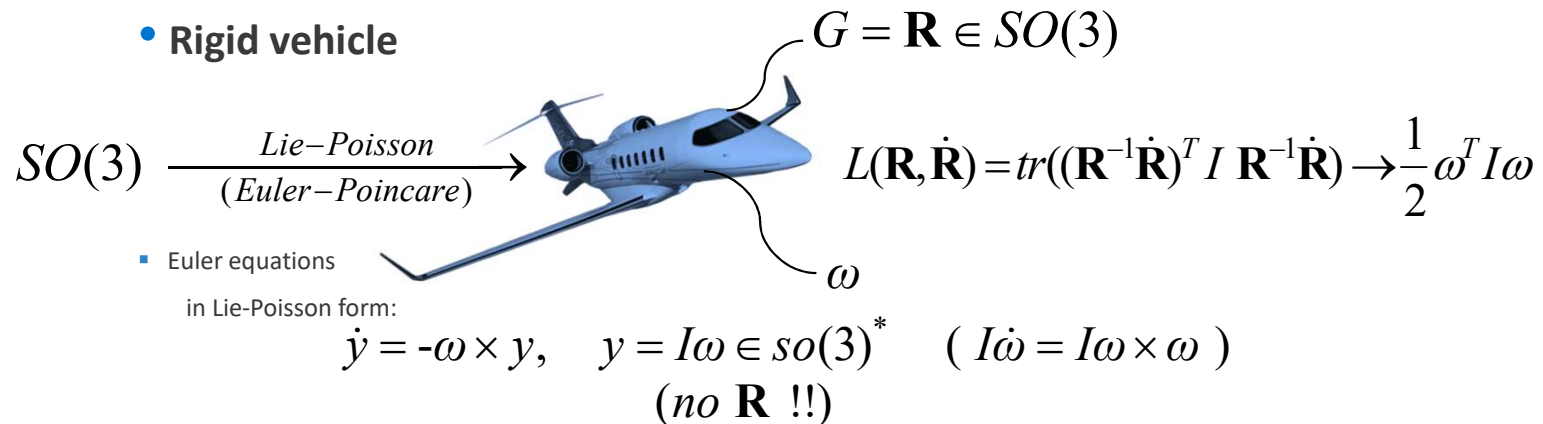


- Velocity field distribution for butterfly wing model

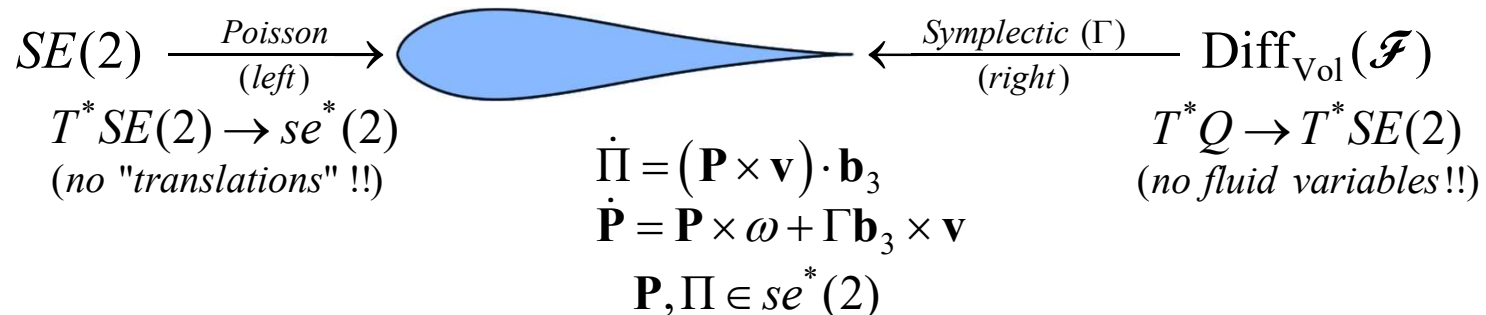
## Fluid - Flying vehicle / 'hybrid' modelling:

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

- Rigid vehicle

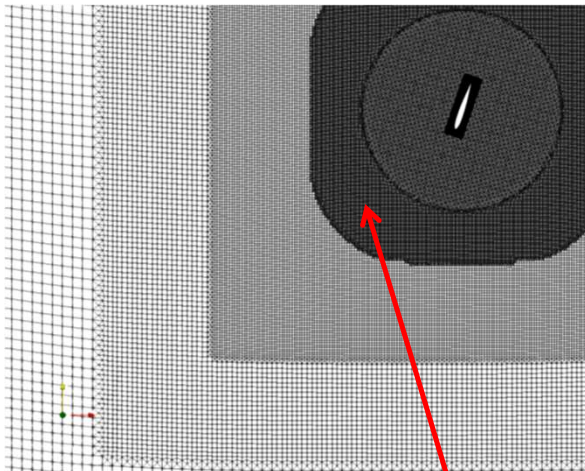


- Rigid vehicle + fluid (planar case)



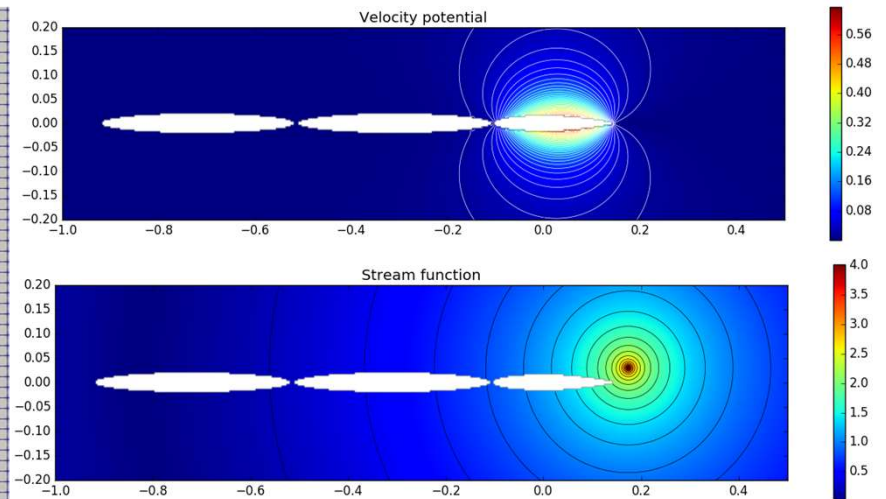
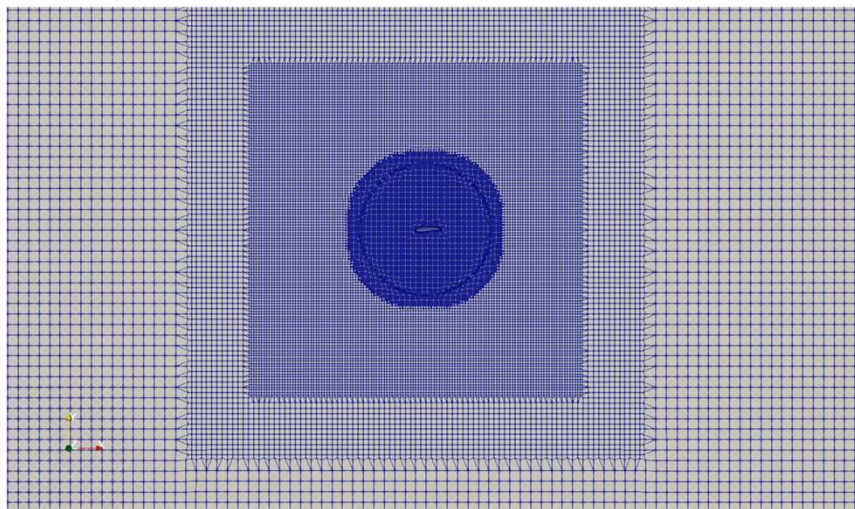
## Fluid volume discretization -> Boundary surface discretization

- Multiple orders of magnitude fewer variables



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

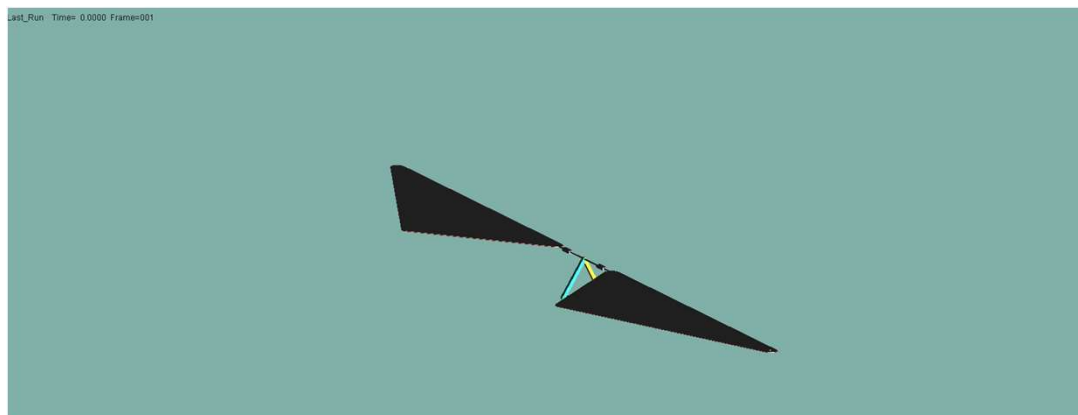
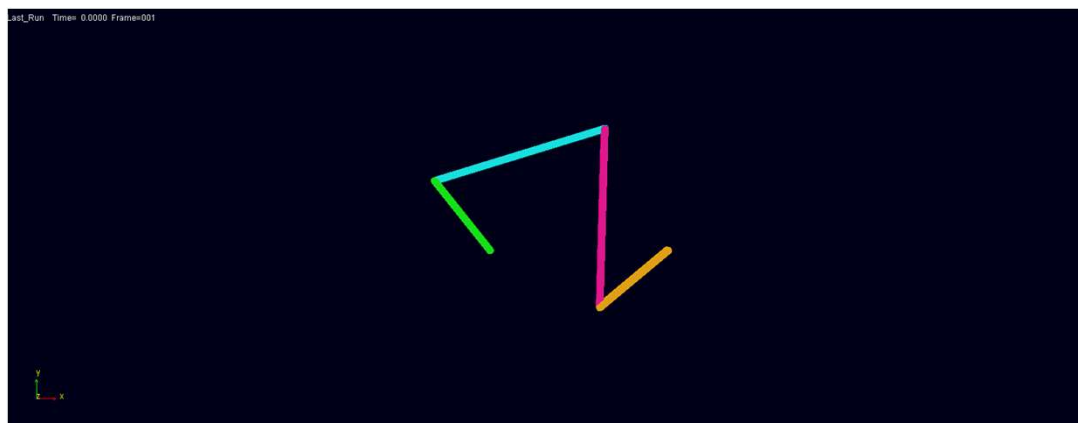
## Finite volume method -> Boundary element method



- 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

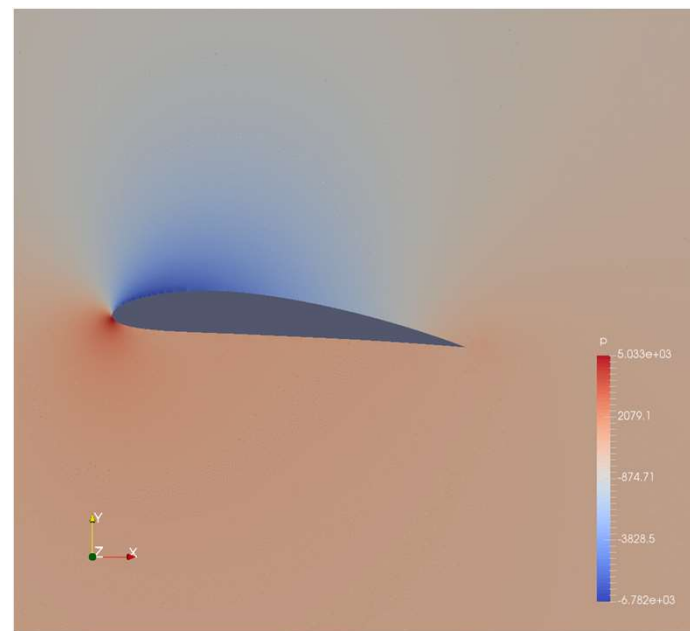
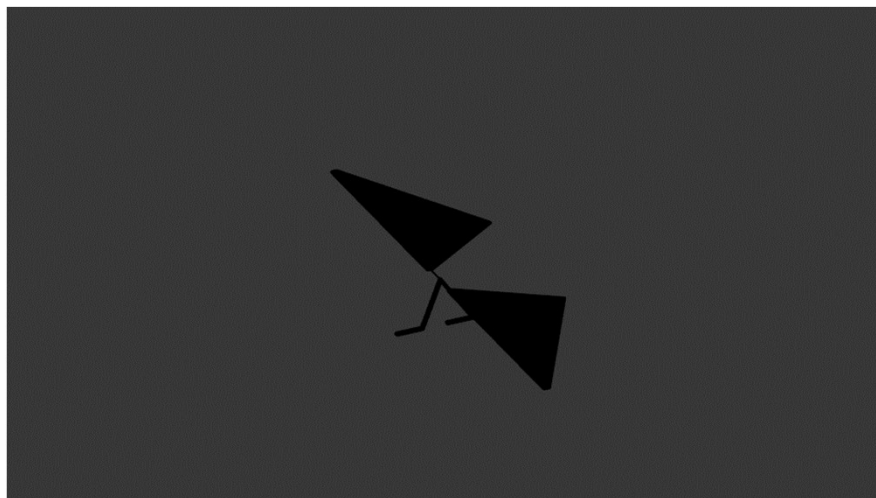


## Variations of wing mechanism....(initial study)



## Dynamic coupling with fluid flow

- MBDyn, OpenFOAM (open source)

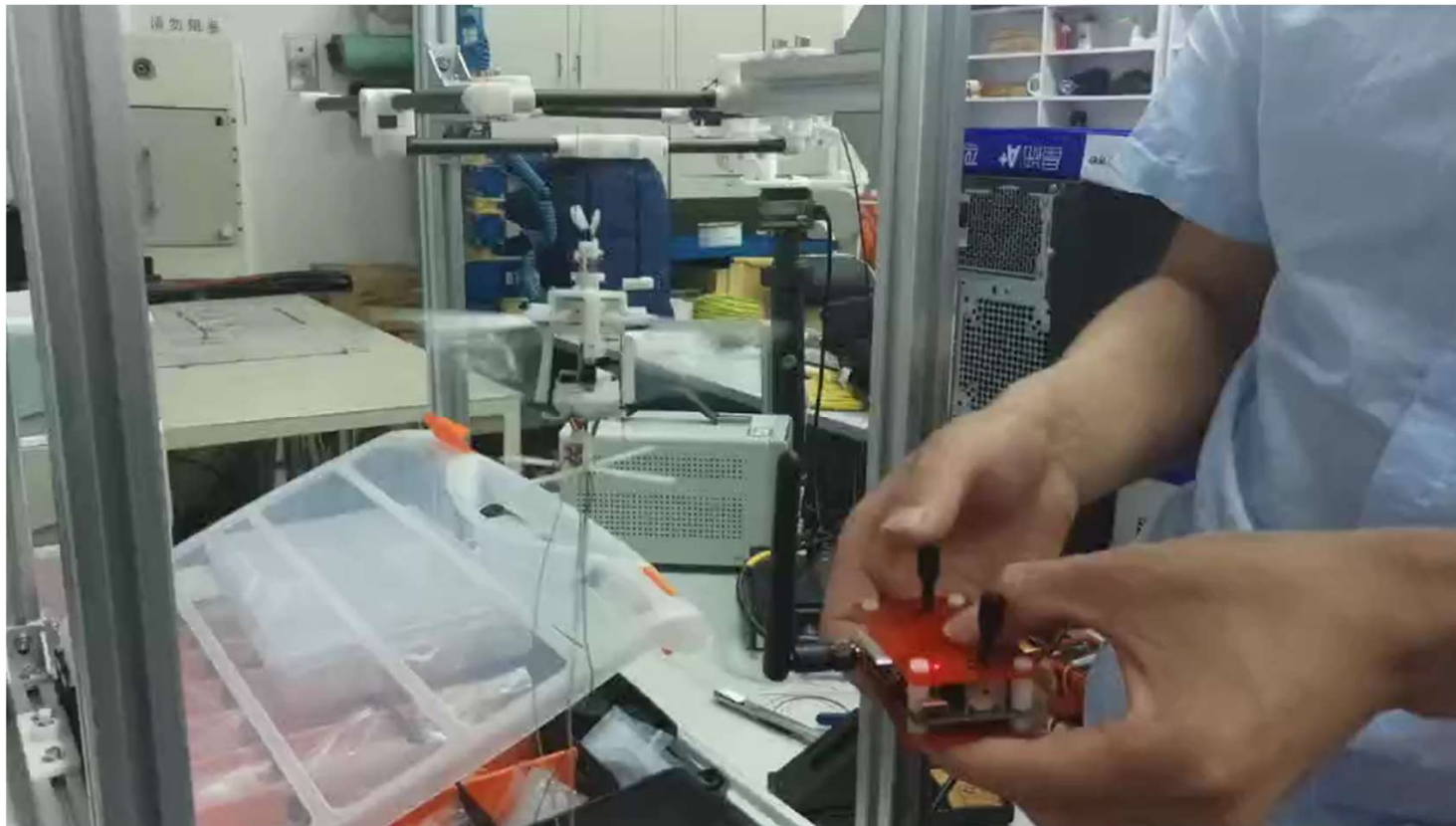




**DEPARTMENT OF AERONAUTICAL ENGINEERING**  
**CHAIR OF FLIGHT VEHICLE DYNAMICS**

**Experiments .../collaboration with:**

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



# FSB



# 100



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- **Thank you for your  
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