Dynamics and control of highly flexible structures for aerospace applications

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PhD course: Space Sciences, Technologies and Measurements (STMS)

Curriculum: Sciences and Technologies for Aeronautics and Satellite Applications (STASA)

XXX series

Outline

- Introduction
  - Gossamer structures
  - Background and test cases
- Membrane with external frame structure
  - Bistable tape springs
  - Mathematical representation
- Preliminary tests
  - Test 1: Elastic and damping properties of the booms
  - Test 2: Boom torques on a fixed spool
  - Test 3: Shock loading at the end of the deployment
- Numerical simulations with control system acting on the boom
- Experimental tests
  - Gravity offloading system
  - Components (electronics and software)
  - Components (mechanical and structural)
  - Results – Non controlled deployment
  - Results – Controlled deployment/retraction
  - Results comparison
- Conclusions

Introduction - Gossamer structures

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Why gossamer structures?

- Advantages:
  - Lower mass and storage volume
  - Lower launch costs
  - Lower manufacturing costs
- Drawbacks:
  - Flexibility
  - Low natural frequencies that can cause instabilities on the central body

Objectives

- Study of the dynamics of highly flexible structures
- Study of its vibrations control systems

Test cases

1. Oscillations control on the membrane with free edges
2. Membrane with external supporting frame. Comparison between controlled and non-controlled deployment. Simple passive damping system.

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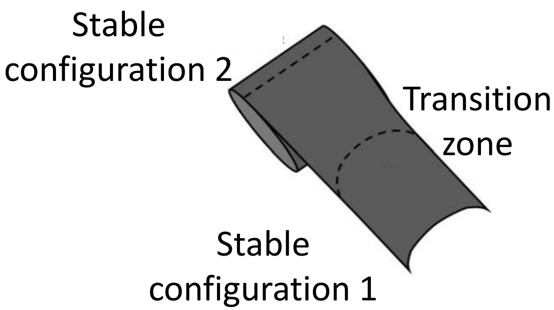
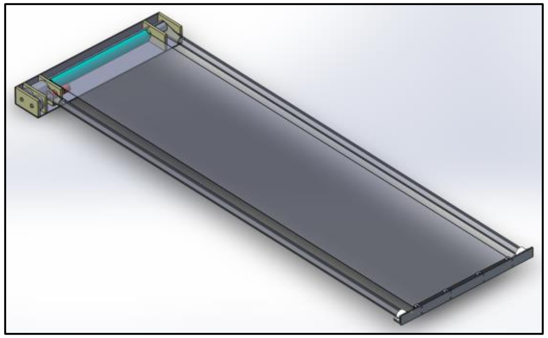
Membrane with external frame structure - Bistable tape springs

Bistable booms:

- are elongated structures made of composite material (e.g. CFRP, GFRP…)
- have low mass per unit length (e.g. 8.6 g/m)
- can be stored in a compact fashion inside the satellite
- present two well-defined stable equilibrium configurations: the deployed (unrolled) and the stowed/coiled one, with the lowest values of stowed strain energy



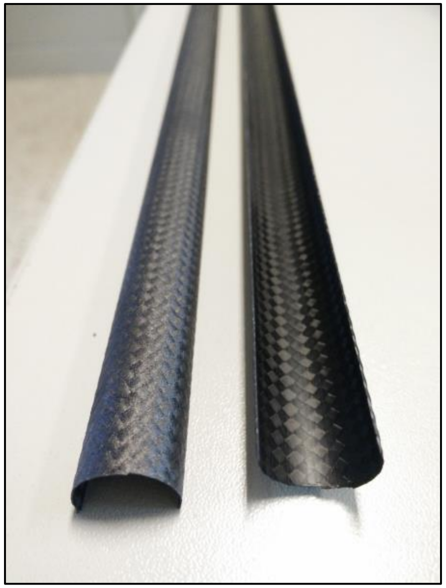


Plain weave CFRP:
- 3K HS Carbon Fibers
- epoxy resin
45° wrt the longitudinal axis

Nominal length: 1 m
Nominal thickness: 0.234 mm
Nominal int. radius: 7.5 mm

Mass: 8.6 g

Membrane with external frame structure – Mathematical representation



Dynamics of the booms:

ABD matrix correlates the applied loads to the laminate strains:

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \begin{bmatrix} 8890.7 & 7525.8 & 0 & 0 & 0 & 0 \\ 7525.8 & 8890.7 & 0 & 0 & 0 & 0 \\ 0 & 0 & 7650.6 & 0 & 0 & 0 \\ 0 & 0 & 0 & 17.8 & 11.6 & 0 \\ 0 & 0 & 0 & 11.6 & 17.8 & 0 \\ 0 & 0 & 0 & 0 & 0 & 13.7 \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix}$$

where the units are N and mm.

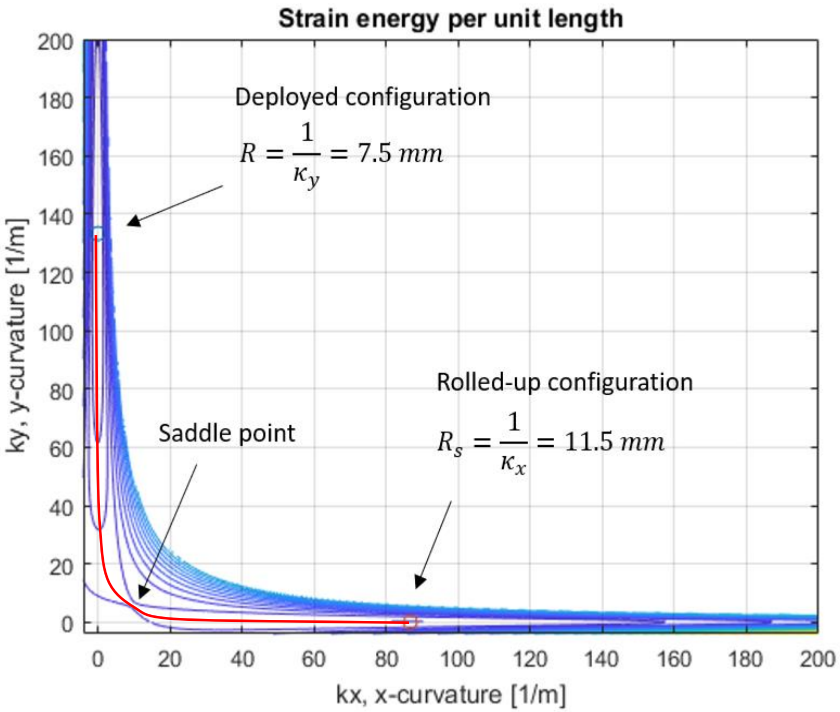
Stability criterion for shells with no coupling between bending and twisting (the structure is bistable for S > 0):

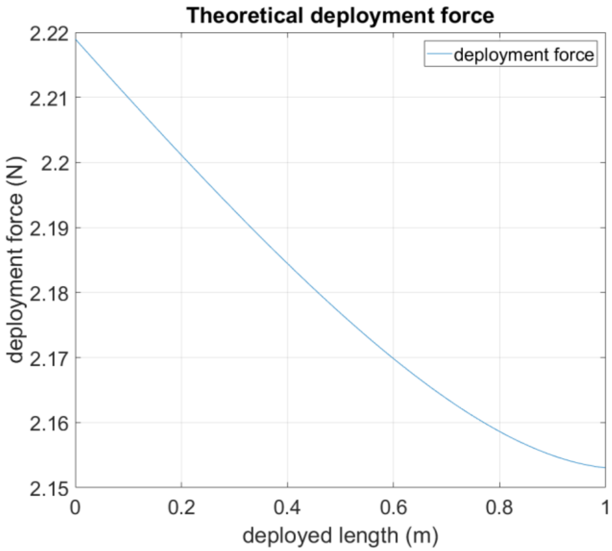
$$S = 4\,\widehat{D}_{66} + 2\widehat{D}_{12} - 2\frac{\widehat{D}_{12}}{\widehat{D}_{12}} = 1.30 > 0$$

Membrane with external frame structure – Mathematical representation

Stowed radius: $R_s = R\dfrac{D_{11}}{D_{12}} = 11.5\ mm$

Approximated torque τ just before full deployment: $\tau = \dfrac{R_H\beta}{2R}\left[D_{22} - \dfrac{D_{12}^2}{D_{11}}\right]$ = 24.8 mNm





Theoretical deployment force:

$$\frac{dU_b}{dL} = \frac{1}{2}\beta R\left(\frac{D_{11}}{R_c^2} - \frac{2D_{12}}{R_cR} + \frac{D_{22}}{R^2}\right)$$

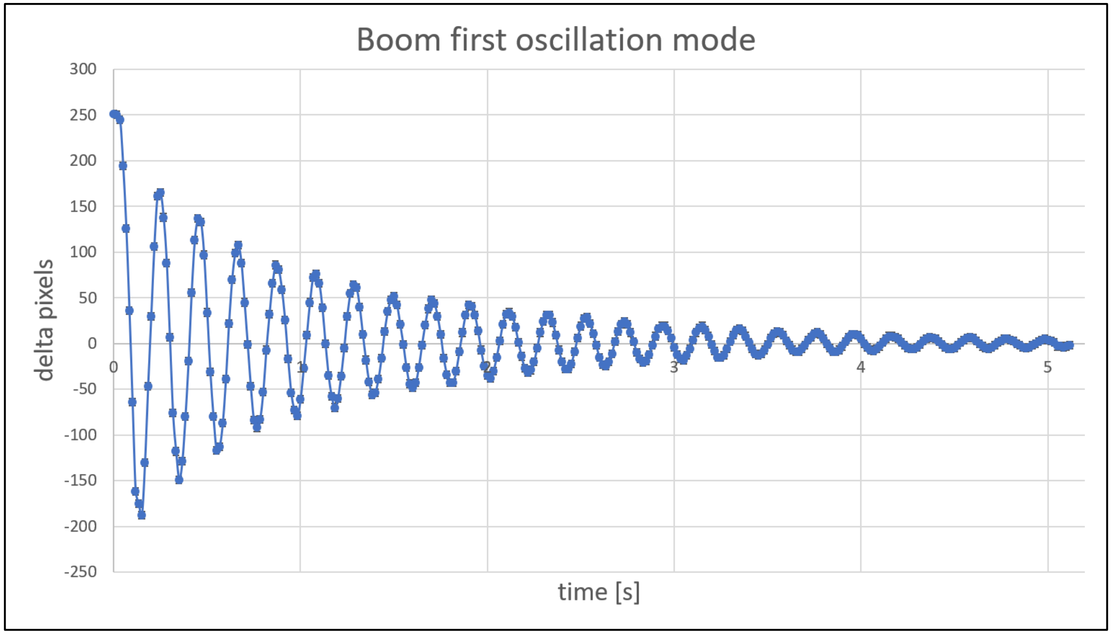
$$2.15\ N < \frac{dU_b}{dL} < 2.22\ N$$

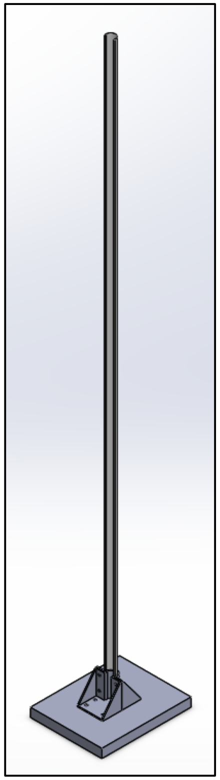
Energy losses due to friction, damping, microcracks and viscoelastic relaxation are not taken into account in theoretical behavior

Outline

Test 1: Elastic and damping properties of the booms

- Experimental evaluation of elastic and damping properties of the boom
- Free length 1 m, fixed on one side
- Sensor: camera with frame rate = 60 frames/s
- Properties calculated with the logarithmic method:
  - Damping ratio: $\zeta = 0.16$
  - Damped frequency: ω_d=4.85 Hz
  - Natural frequency: ω_n=4.92 Hz

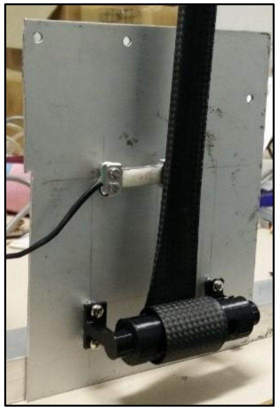


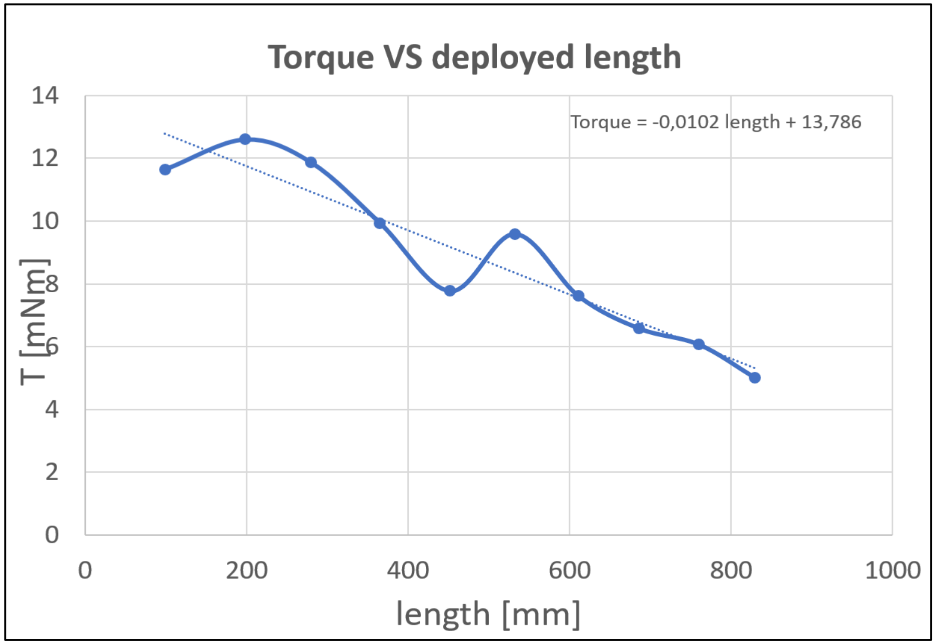


1 pixel = 0.15 mm

Test 2: Boom torques on a fixed spool

- Measurements with a 100g load cell
- Experimental forces result about 10 times smaller than the theoretical force – compatible with what was observed in other similar experiments by other researchers
- Energy losses due to friction, damping, microcracks and viscoelastic relaxation

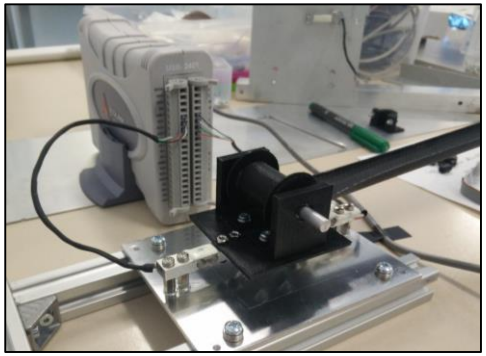


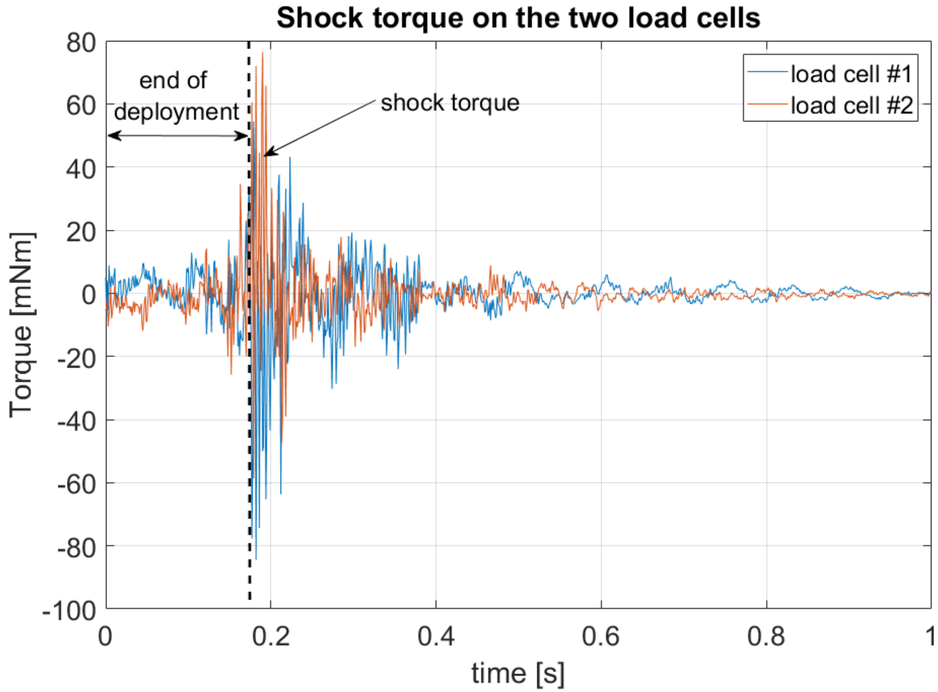


- Irregular curve because of imperfections in the manufacturing of the boom and/or non perfect verticality during tests.
- Experimental torque results are about ¼ of the theoretical torque.
- The resulting torque values were used to select the motor to drive the spool in later experiments

Test 3: Shock loading at the end of the deployment

- Measurements with two 780g load cells, removing all the static components of the measurements (weight of the structure, boom…)
- Partial deployment of the boom (the last 21.5 cm in this case), with the tip suspended by a cord.
- The results are compatible with other similar experiments by other researchers on different woven materials (GFRP)





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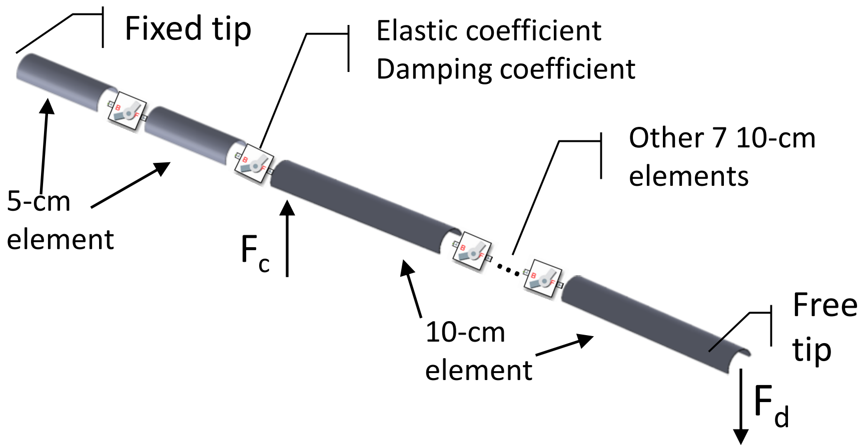
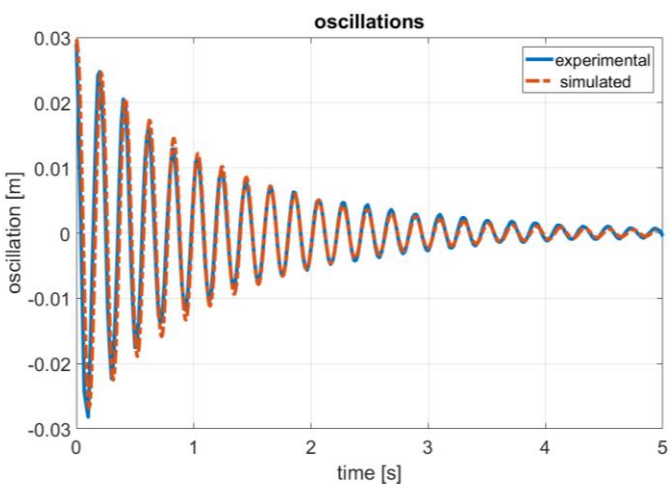
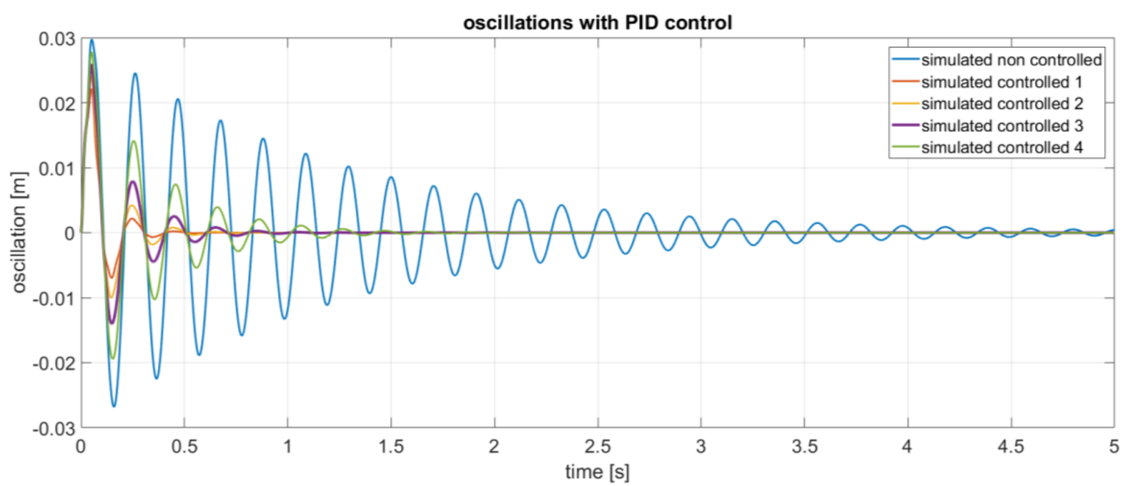
Numerical simulations with PID control system acting on the boom

- Simple model where the boom is simulated as a series of masses, springs and dampers, fixed on one side, free on the other.
- With the elasticity and damping coefficients applied it showed a very similar behavior to results of preliminary test 1
- Applying a control force with a PID controller on the boom it damps out the oscillations quickly







Different values for the Kp, Ki, Kd coefficients

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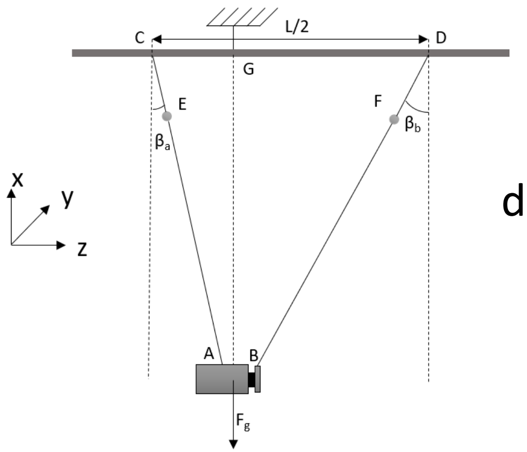
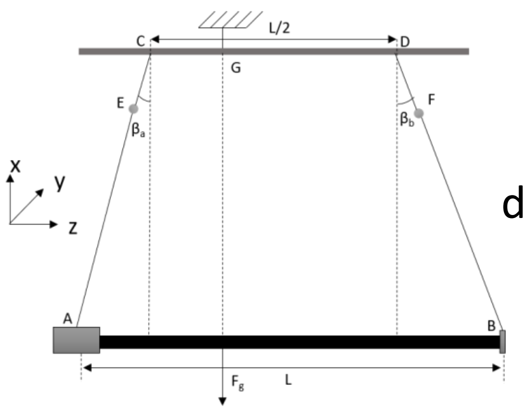
Experimental tests – Gravity Offloading System

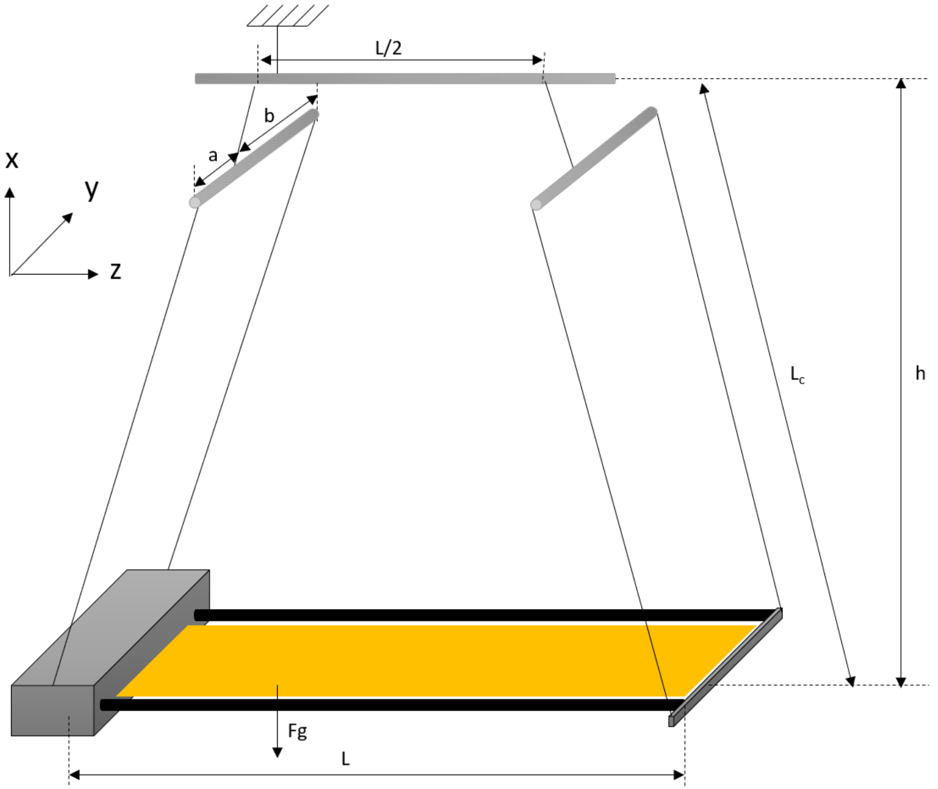
- Used to simulate absence of gravity
- The vertical component of the tension vector of the cords is equal to the $F_g = m*g$ of the masses
- Length of the cables: 4.94 m
- Deployer mass (m_A) >> tip mass (m_B), $\beta_A << \beta_B$



Before deployment

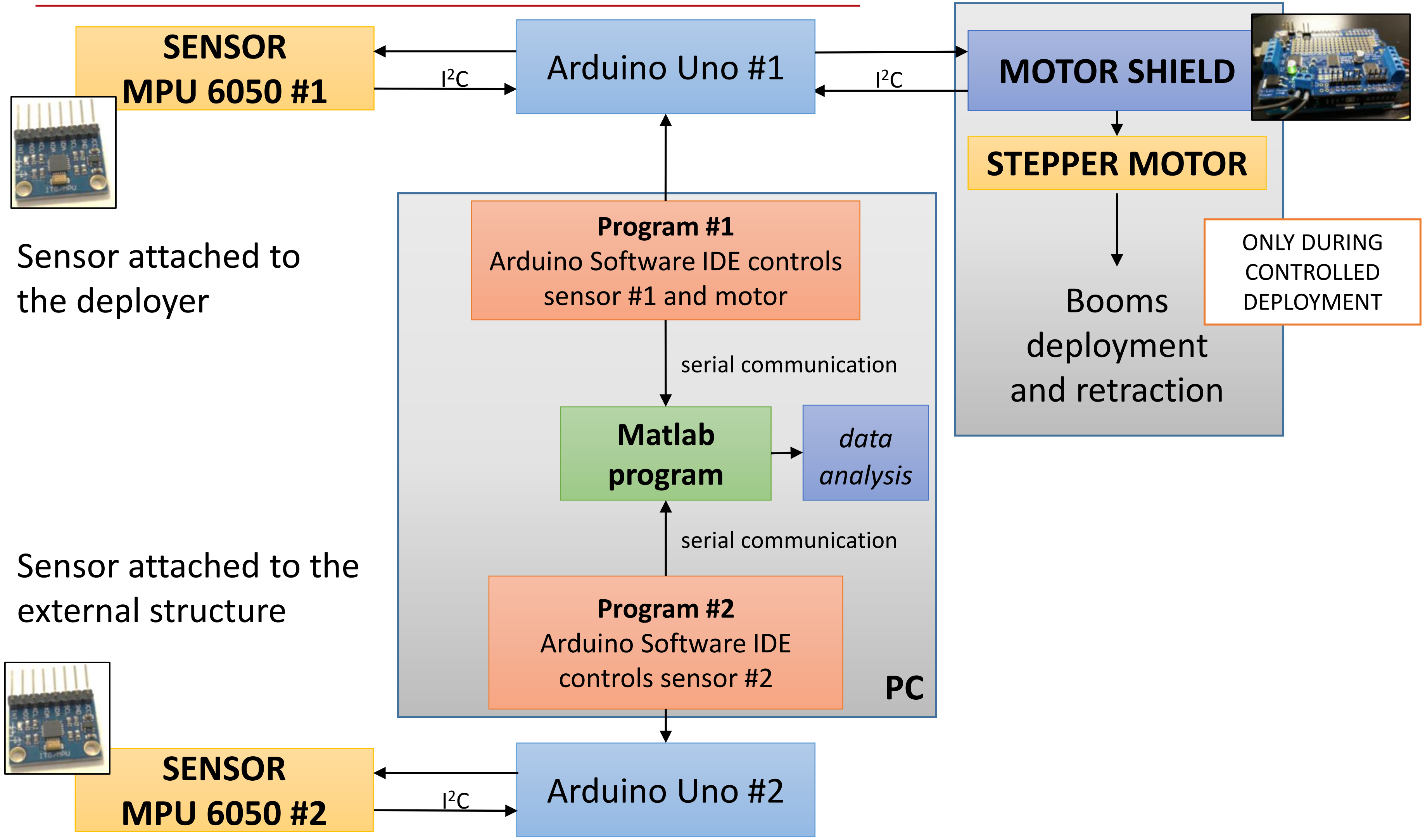


After deployment



Images not to scale

Experimental tests – Components (electronics and software)



Experimental tests – Components (mechanical and structural)

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Experimental tests – Results
Non controlled deployment

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Experimental tests – Results
Non controlled deployment

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Frequency (Hz)

Experimental tests – Results
Controlled deployment/retraction

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Experimental tests – Results
Controlled deployment/retraction

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Experimental tests – Results comparison

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Frequency (Hz)

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Conclusions

- What was done:
  - Numerical simulations on a free membrane (not presented here)
  - Numerical simulations and experimental tests on a deployable structure (deployer + booms)
  - Additional numerical simulations that were not presented here

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THANKS FOR YOUR ATTENTION!