Towards the mechanical and control-oriented optimization of micromechatronic systems for robust control

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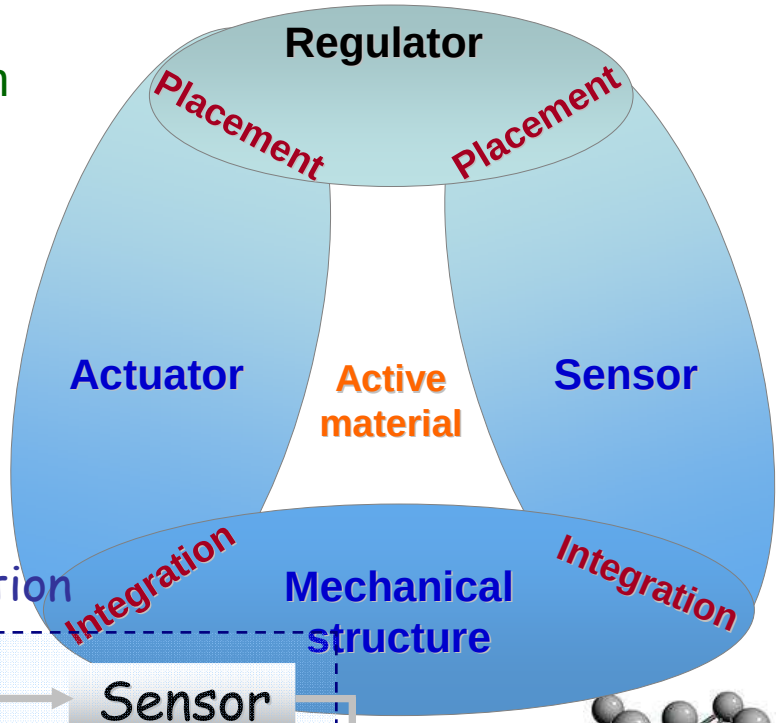
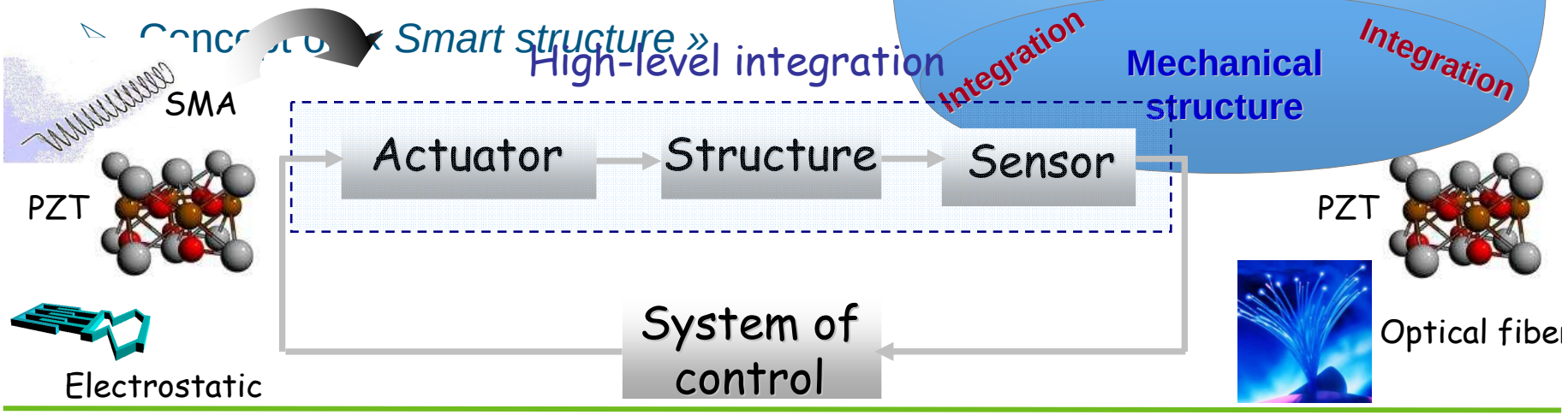
Integration in micromechatronics

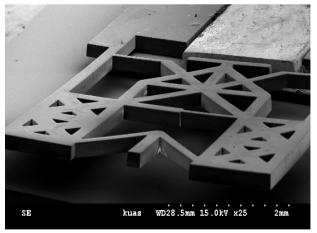
- Micromechatronic
  - ✓ interdisciplinary scientific area
  - ✓ microrobotic : one application domain
- Evolution to the concept of adaptronics
  - ✓ functional elements of a classic regulation process into one single system
  - ✓ functional integration
- Concept of « *Smart structure* »



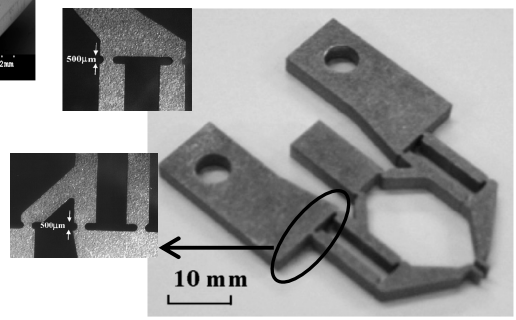


Design specificities of microrobots

- Mechatronic design
  - ✓ flexible mechanisms
    - avantage of monolithic structures
      - fabrication,
      - simplified maintenance
    - no backlash
  - ✓ actuation and sensing functions
    - weak encumbrance but high resolution
    - active material technologies

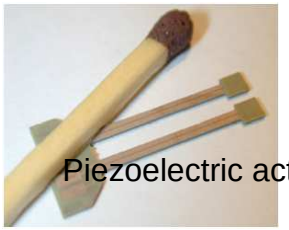


[Huang 06]



[Nah 07]

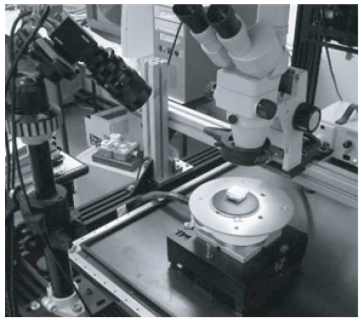
- Control of microrobots
  - ✓ scale effects
    - difficulties of obtaining dynamic model
    - difficulties of sensor integration
    - environment influence and variability
  - ✓ non-linear behavior of active materials



Piezoelectric actuator

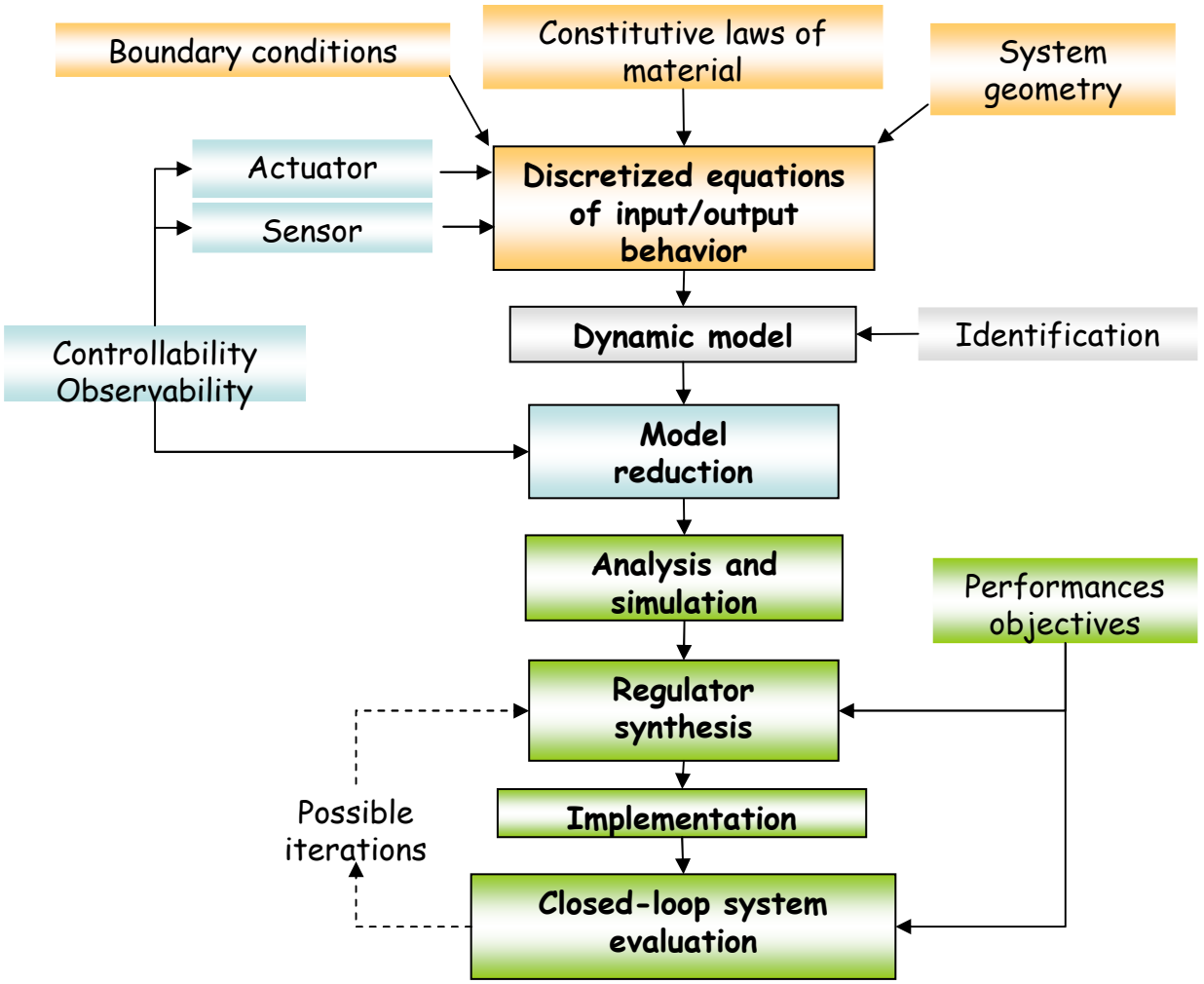
[Agnus 02]

- Multidisciplinary design
  - ✓ complex specifications
  - ✓ non-intuitive design



[Shacklock 05]

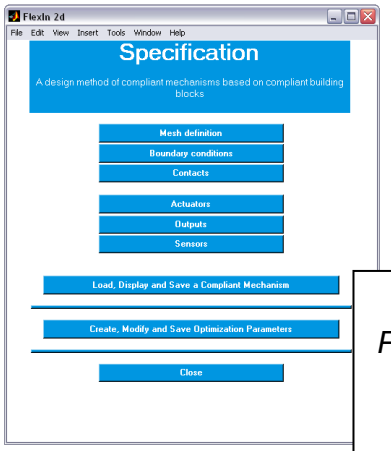
Analysis and synthesis approach



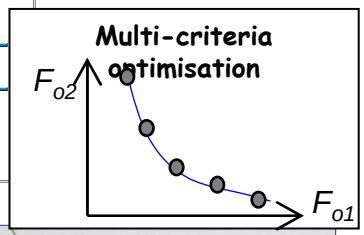
Positioning towards the problem (1/2)

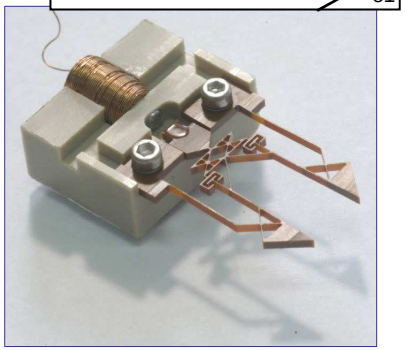
➢ Development of an optimal synthesis method : FlexIn

FlexIn



[Bernardoni 04]





✓ design of 2D monolithic flexible structures with integrated actuation

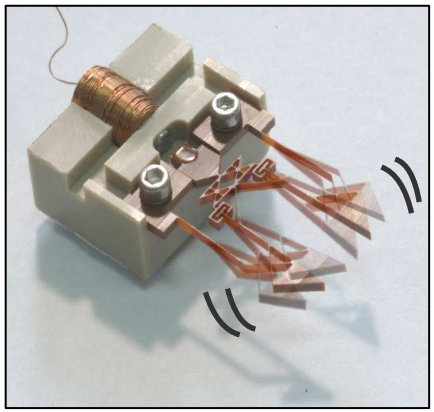
✓ choice of the piezoelectric actuation

- good performances in the micromechatronic sense

  resolution, force, bandwidth, …
- electromechanical behavior known
  - mixte FE formulation
- control by voltage
- known prototyping process

Positioning towards the problem (2/2)

- Integration of the dynamic part in the method
  - ✓ description through a dynamical model
    - prediction of the frequency response function
  - ✓ new criteria
    - orientation of the frequency response function

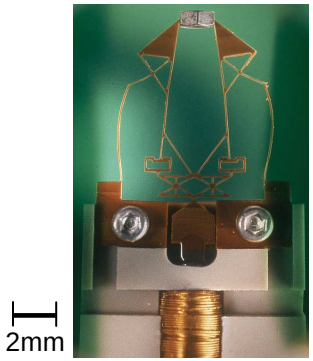


Plan

1. **Building blocks method**
2. Optimal synthesis of active structures under FlexIn
3. Optimal synthesis with dynamic considerations
4. Design and control of a micro-actuator prototype
5. Conclusion and perspectives

General approach

➢ Flexible structures design with FlexIn



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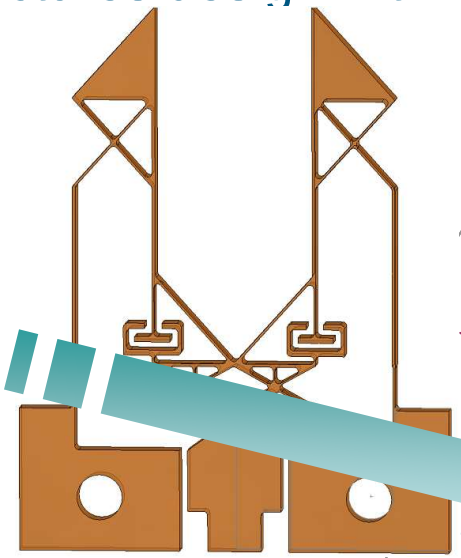
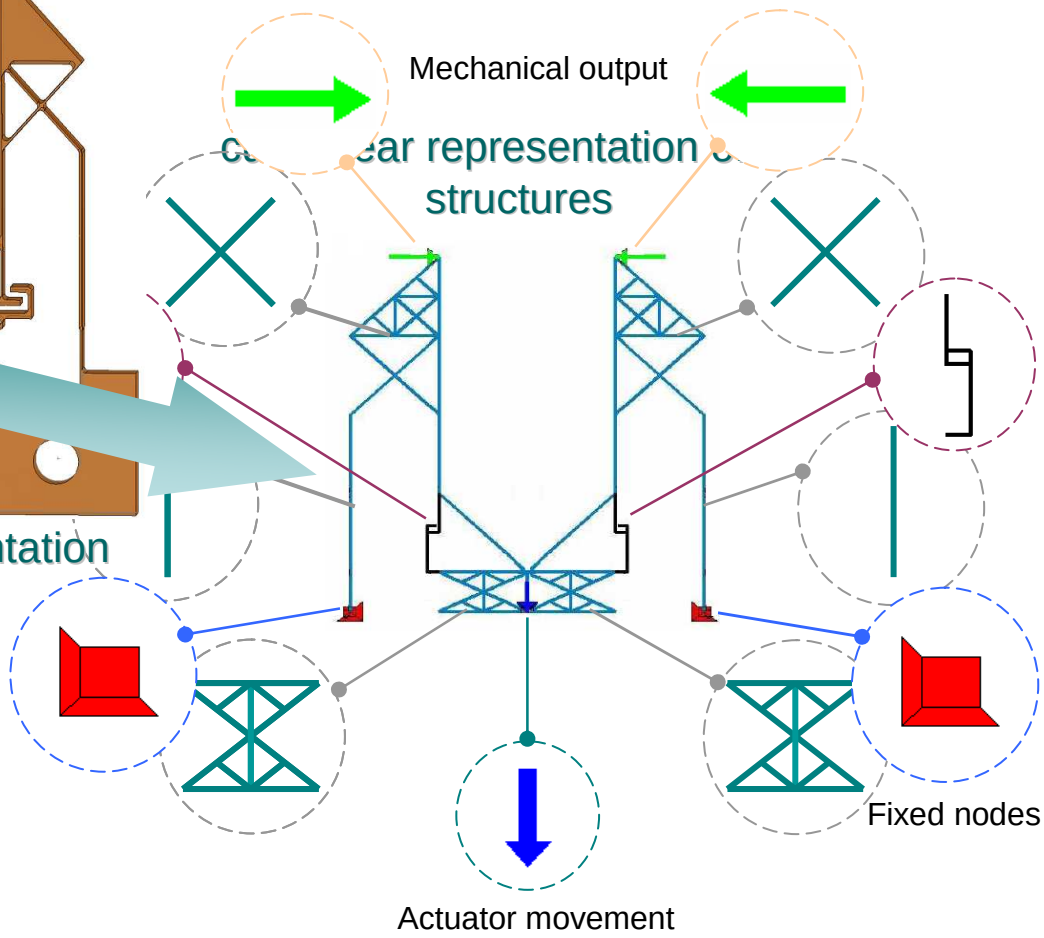

CAD representation

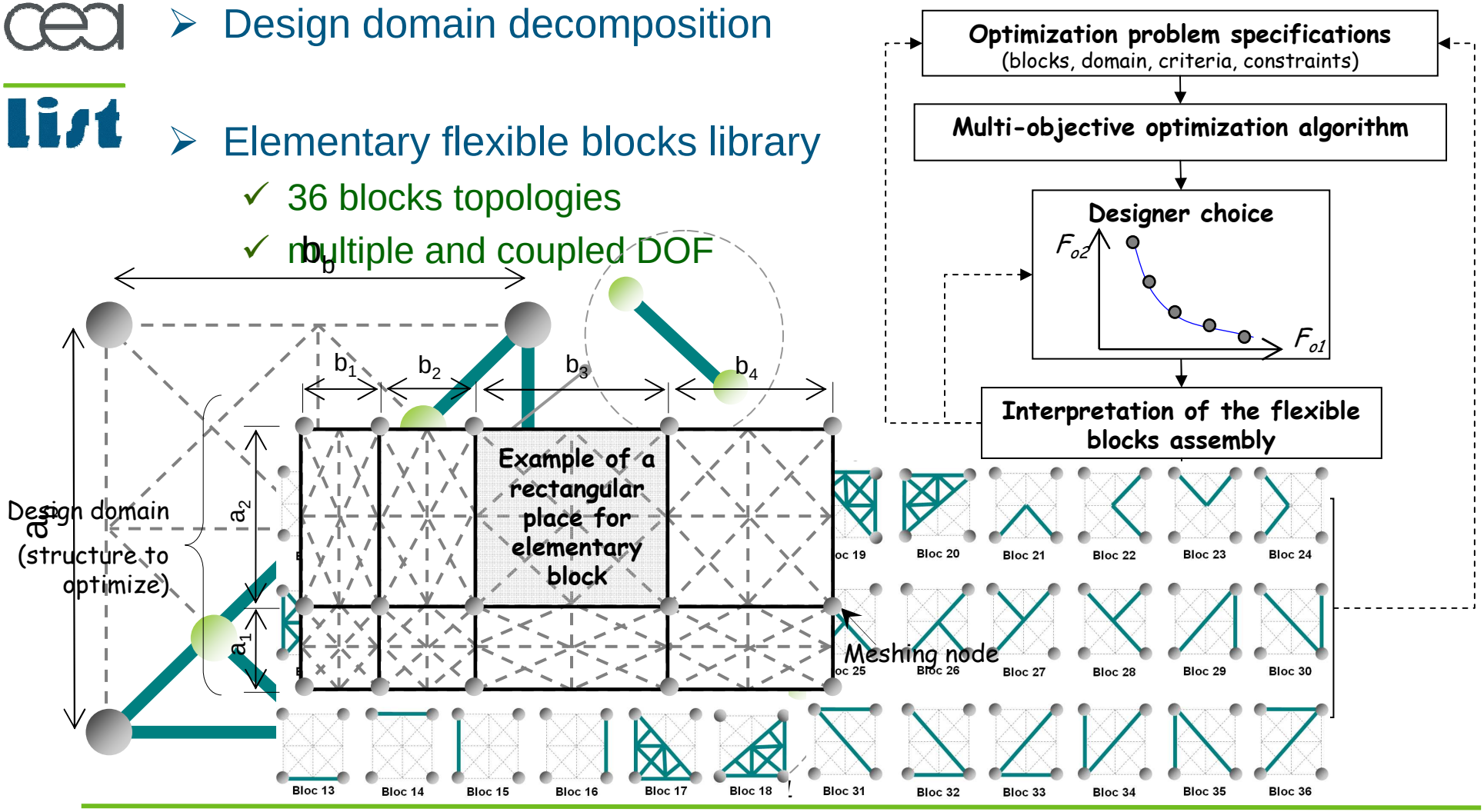


Cutting out into elementary building blocks :

- ✓ elementary building block
- ✓ actuator boundary conditions
- ✓ contacts
- ✓ fixed nodes boundary conditions
- ✓ mechanical output

Building blocks method

- Design domain decomposition
- Elementary flexible blocks library
  - ✓ 36 blocks topologies
  - ✓ multiple and coupled DOF



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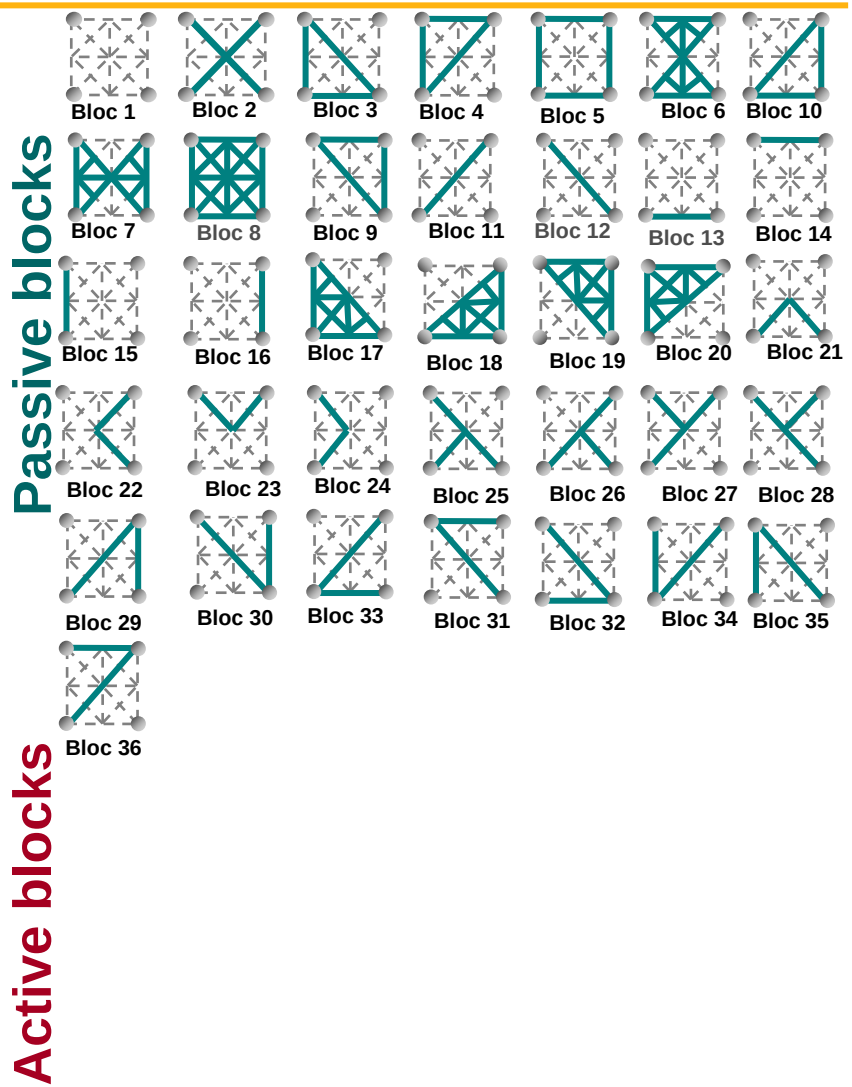
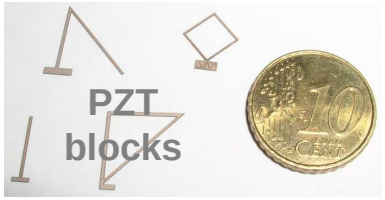
Implementation of an active library

- Active blocks of various topologies
  - ✓ actuation mode
  - ✓ distributed planar actuation
  - ✓ controlled by electric voltage U_p



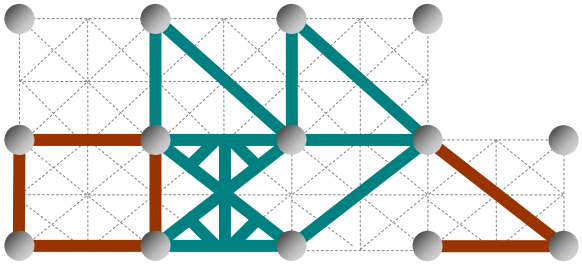
Implementation under FlexIn

- Elementary active blocks
  - ✓ Assembly of elementary piezoelectric beam



- Code of a complete structure
  - ✓ monolithic structure : assembly of active and passive blocks
  - ✓ active/passive topologies

active / passive topologies



Integer matrix

1	3	3	0
5	6	12	33

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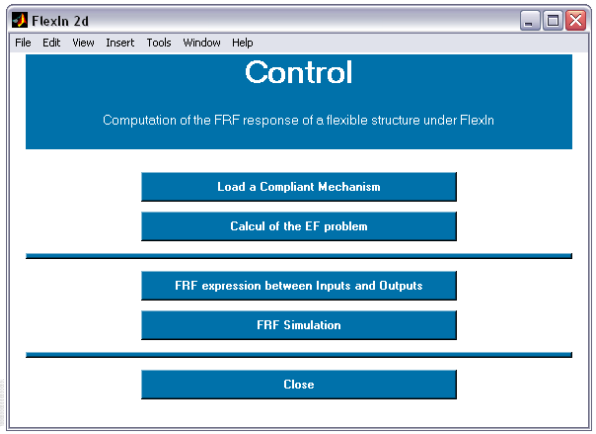
Implementation of the dynamic part

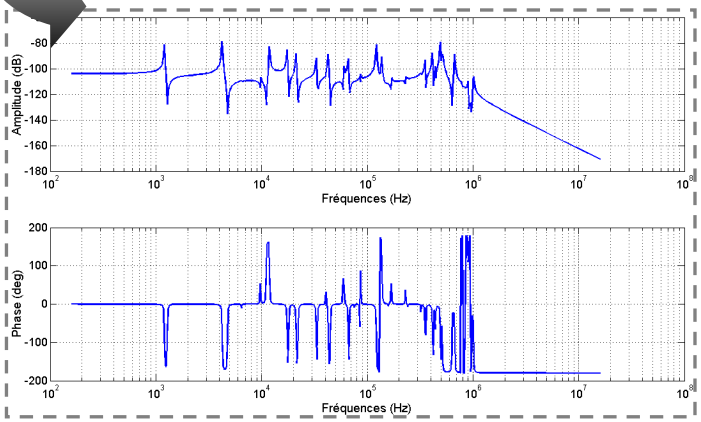
Second order dynamic model

- ✓ transfer matrix : modal expansion

$$\mathbf{y} = \sum_{i=1}^{p} \frac{\mathbf{F}_g \mathbf{Q}_i \mathbf{Q}_i^t \mathbf{E}_g}{s^2 + 2\xi_i \omega_i s + \omega_i^2} \mathbf{u}$$

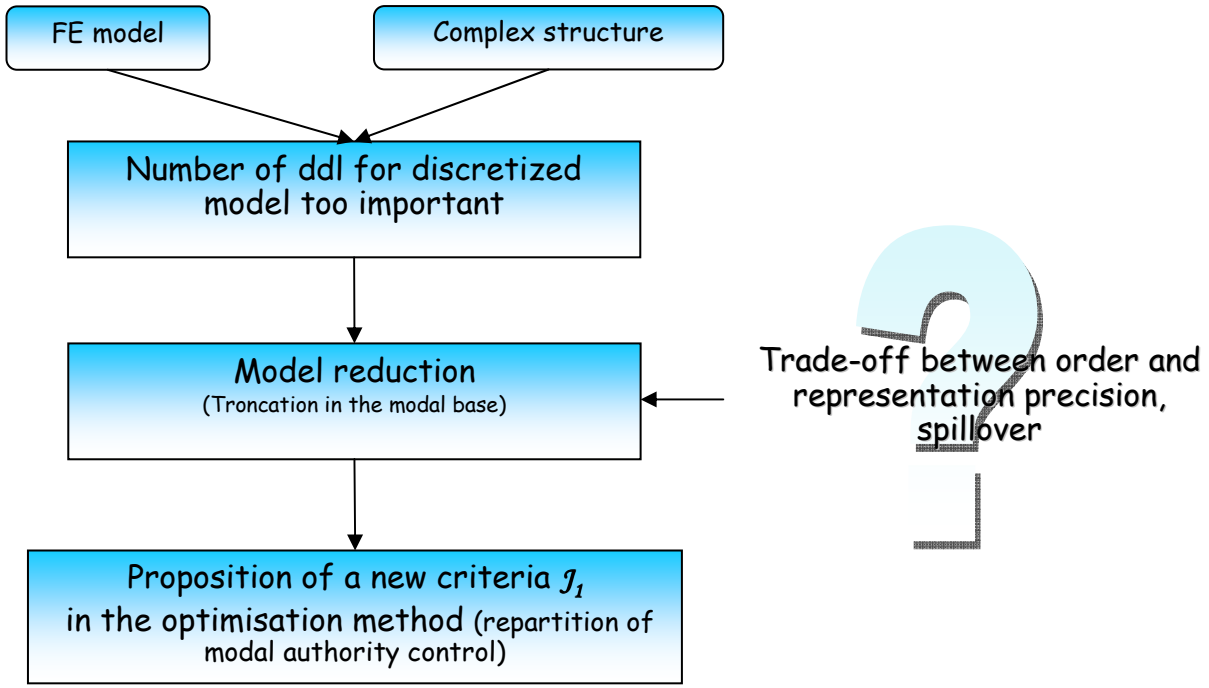
- ✓ input/ouput frequency reponse simulation





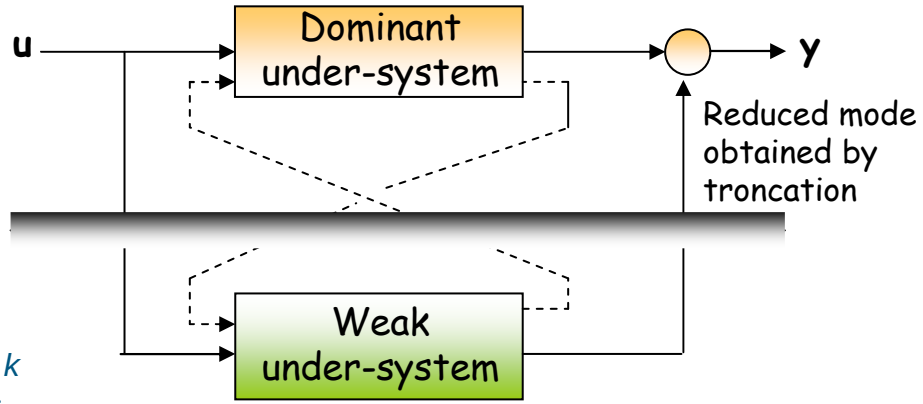
identification of flexible structures

➢ Reduction of the number of dominant modes



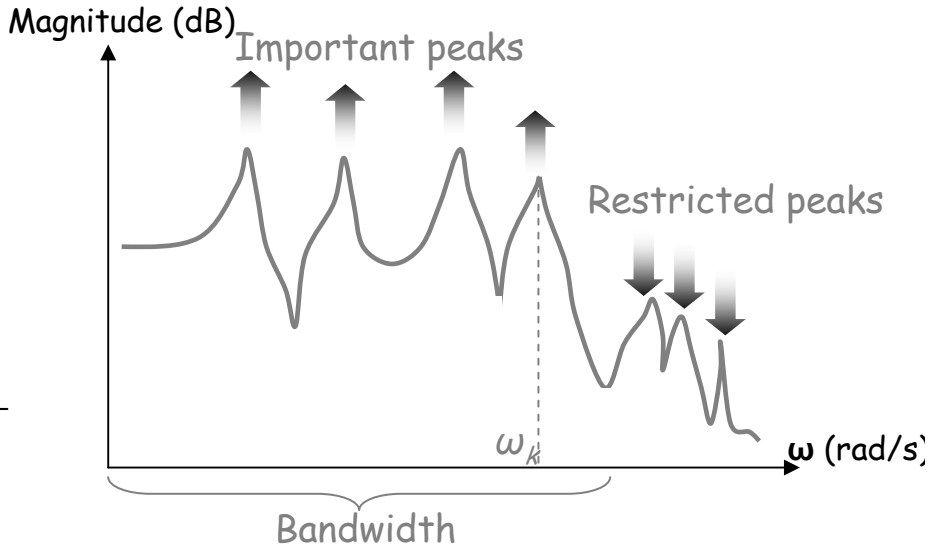
Identification of flexible structures

- Reduction in the modal base
  - ✓ *Moore* method expressed directly in the diagonal modal base
  - ✓ characterization of the joint controllability/observability degree



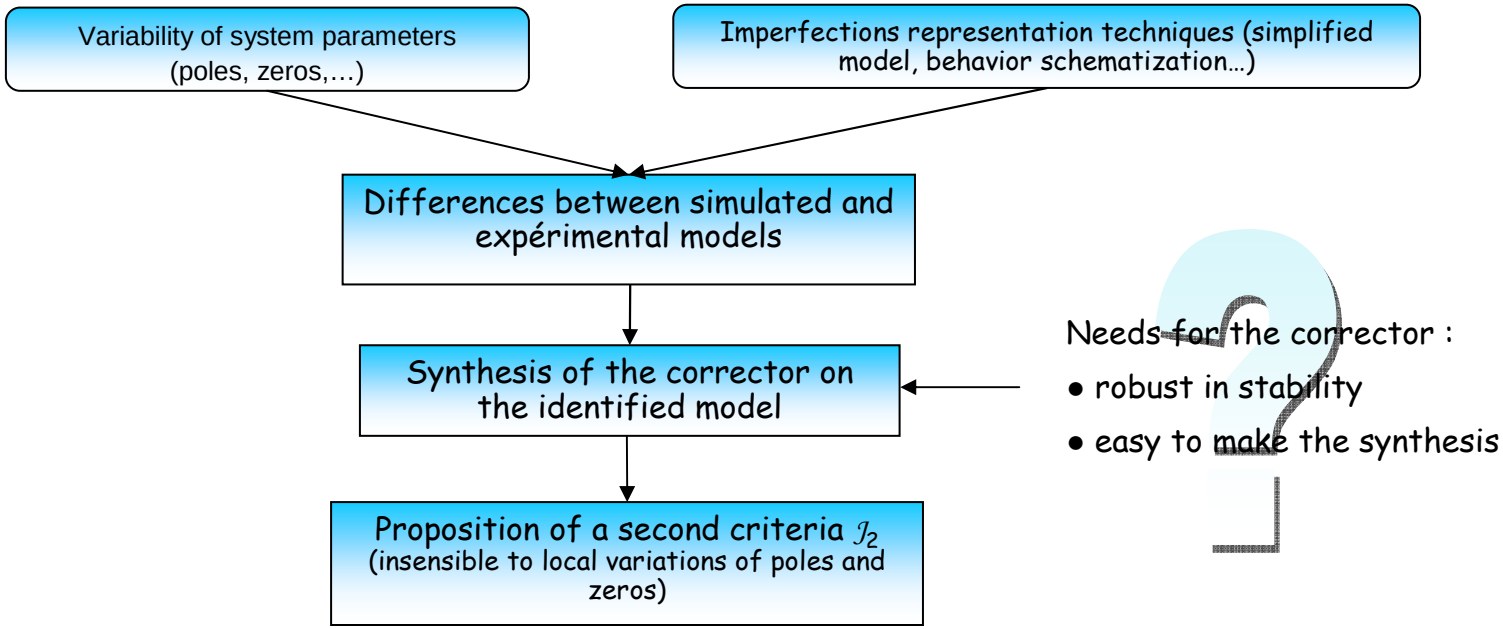
- Expression of the numeric criteria J_1^k
  - ✓ choice of the number *k* of dominant modes
    - maximization of control authority of the *k* first modes
    - minimization of modes out of the bandwidth
  - ✓ graphical interpretation by using $\|.\|_\infty$ norm (SISO)

$$J_1^k = \frac{\sum_{i=1}^{k} \sigma_i}{\sum_{i=k+1}^{N} \sigma_i}$$



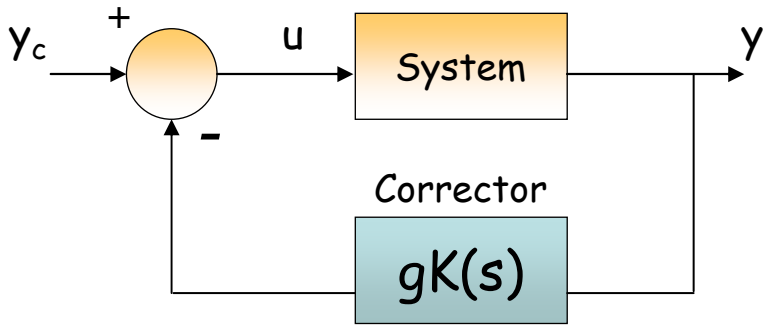
Control of flexible structures

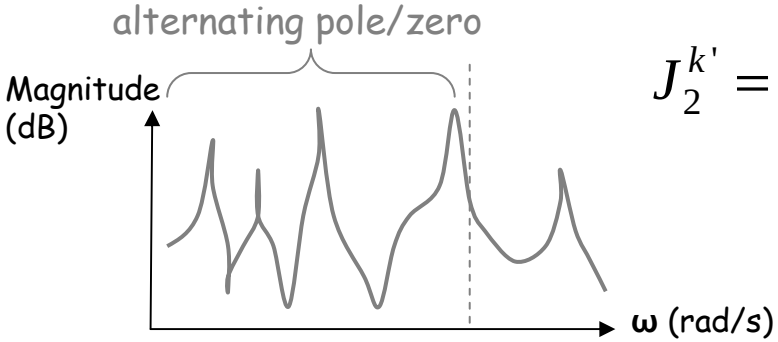
➢ Analysis of frequential properties of flexible structures



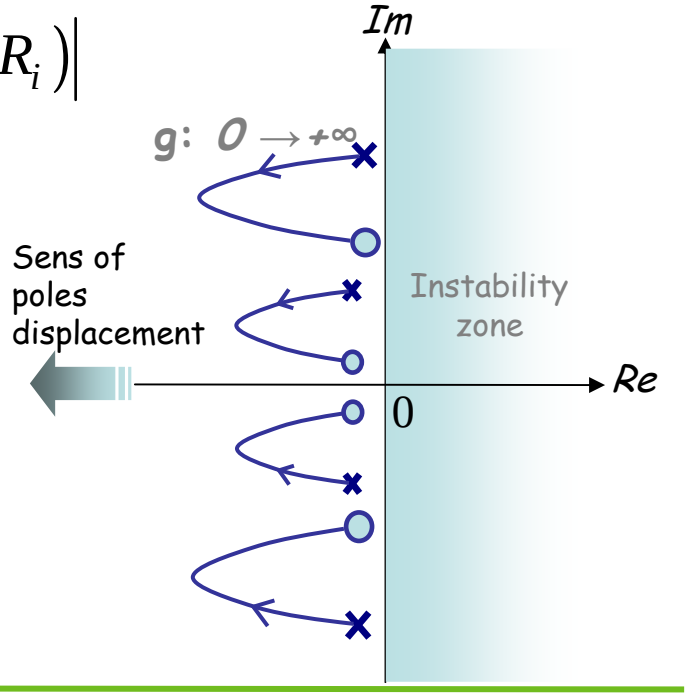
Control of flexible structures

- Influence of the feedback gain *g*
  - ✓ feedback scheme for control
  - ✓ trajectory of poles in closed-loop
  - ✓ pole/zero alternating properties
    - stability loops in closed-loop





$$J_2^{k'} = \sum_{i=1}^{k'} \left| sign\left(R_i\right) \right|$$



- Expression of the numerical critria $J_2^{k'}$
  - ✓ criteria expressed from the modal expansion of the input/output transfer
  - ✓ choice of the number *k'* of considered modes for the alternating poles/zeros

Plan

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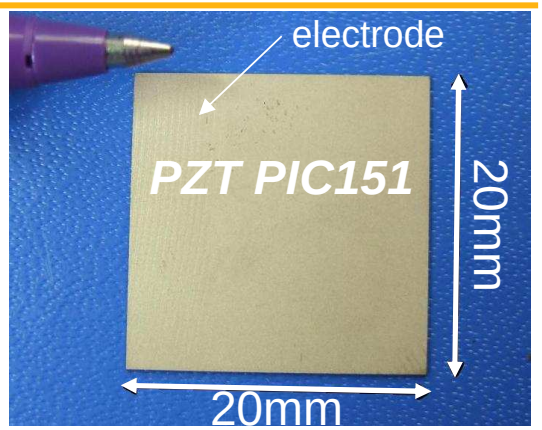
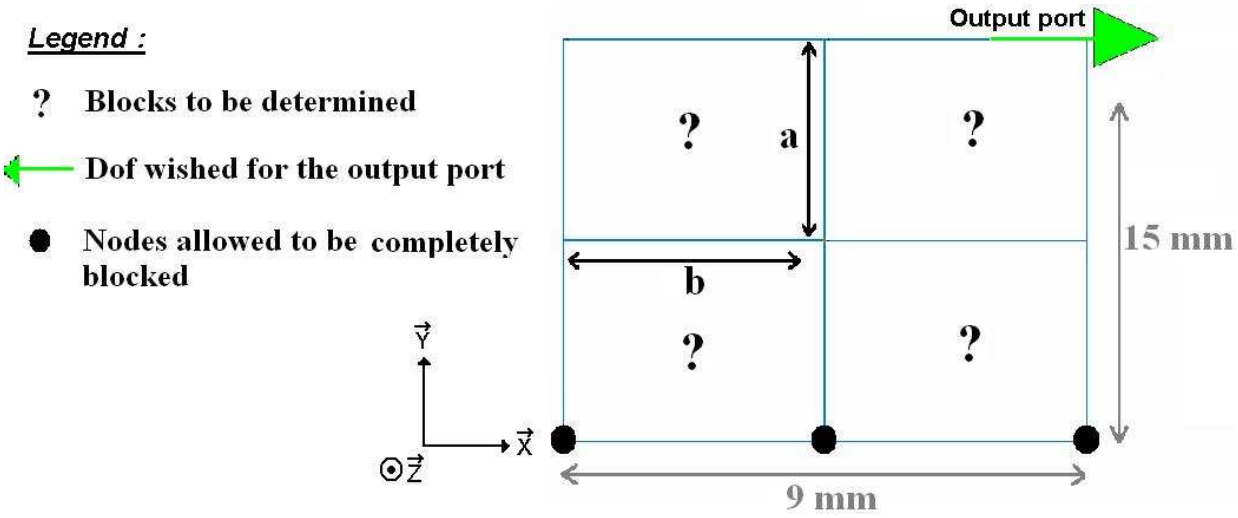
Design of a monolithic microgripper

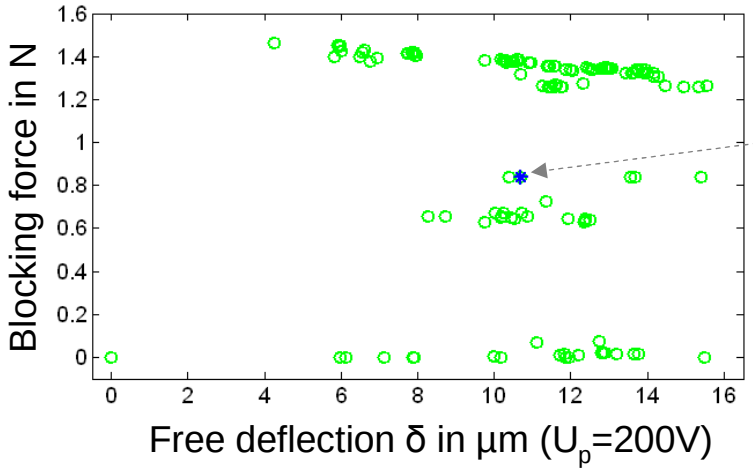
- Multi-criteria optimisation
  - ✓ mechanical in static mode
    - Blocking force *F*
    - Free deflection δ
  - ✓ control-oriented $\mathcal{J}_1^2$ et $\mathcal{J}_2^2$
  - ✓ Optimisation parameters
    - $1 \leq N$ active blocks ≤ 4
    - $U_p = 200V$
    - $1 \leq N$ fixed nodes ≤ 3

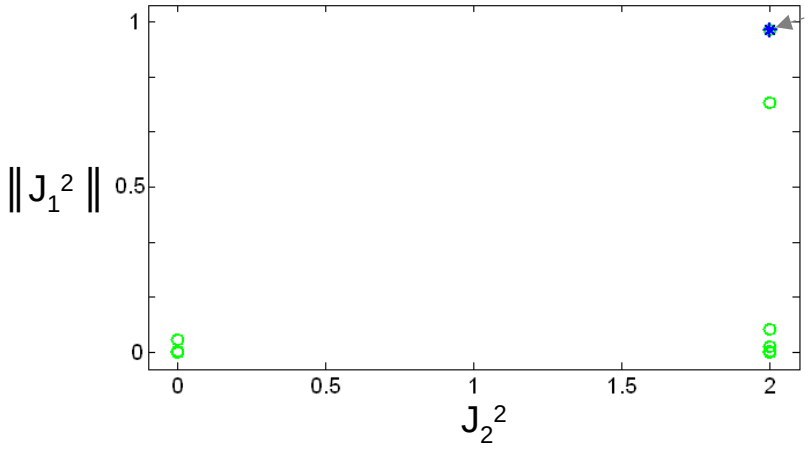


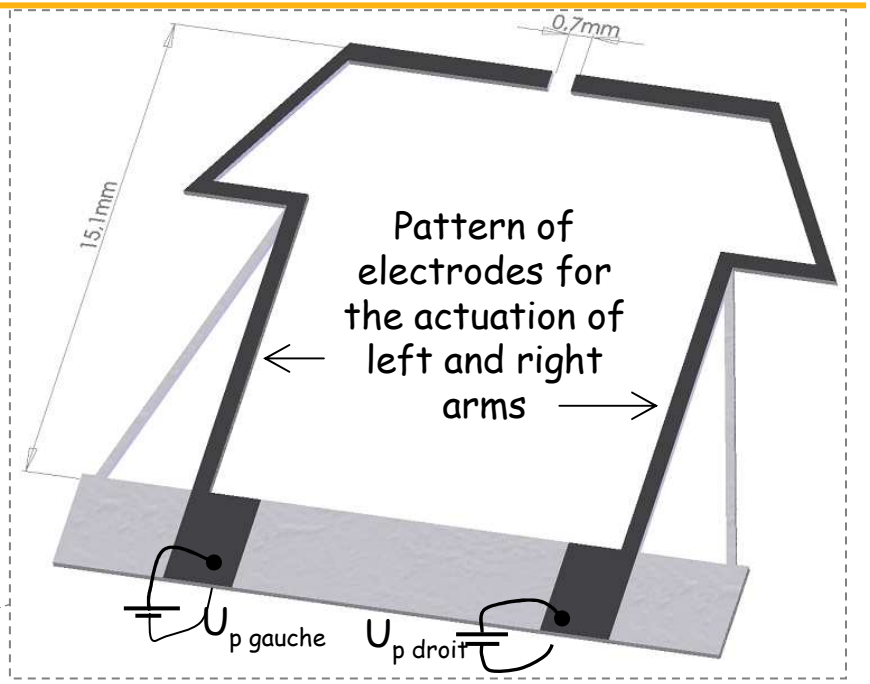


Selection of a pseudo-optimal solution

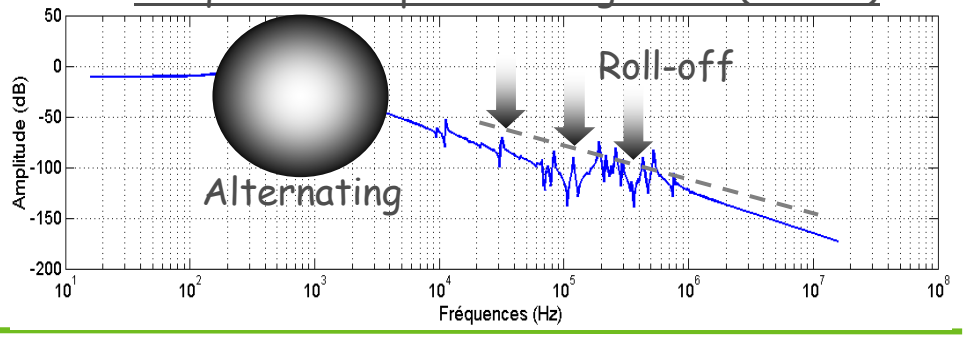
➢ Pareto fronts







Frequential response in magnitude (FlexIn)



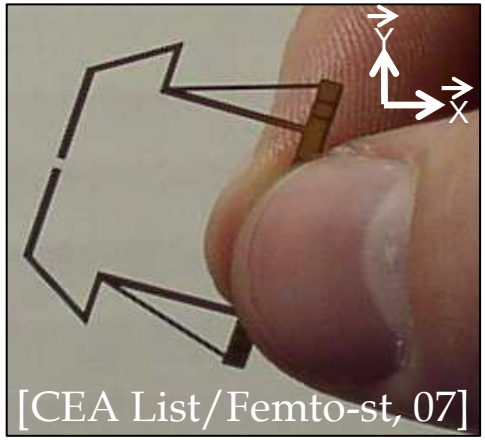
Experimental set-up

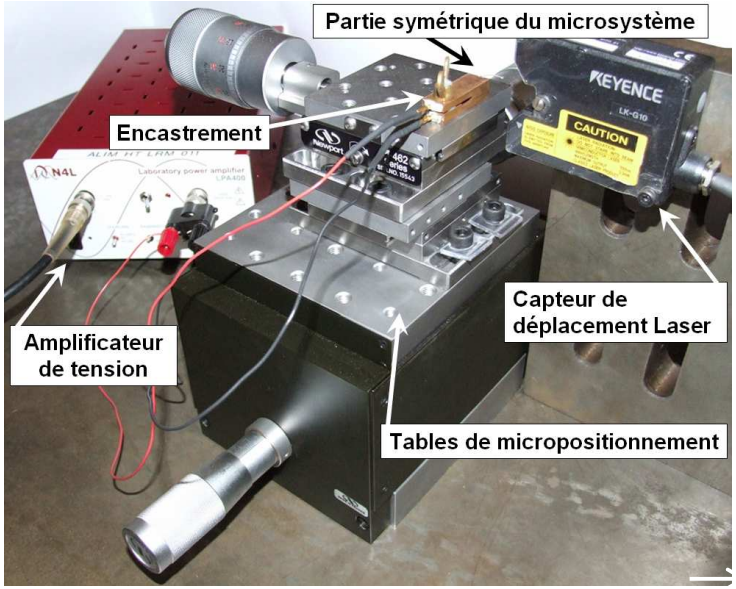
- Piezoelectric prototype
- Set-up

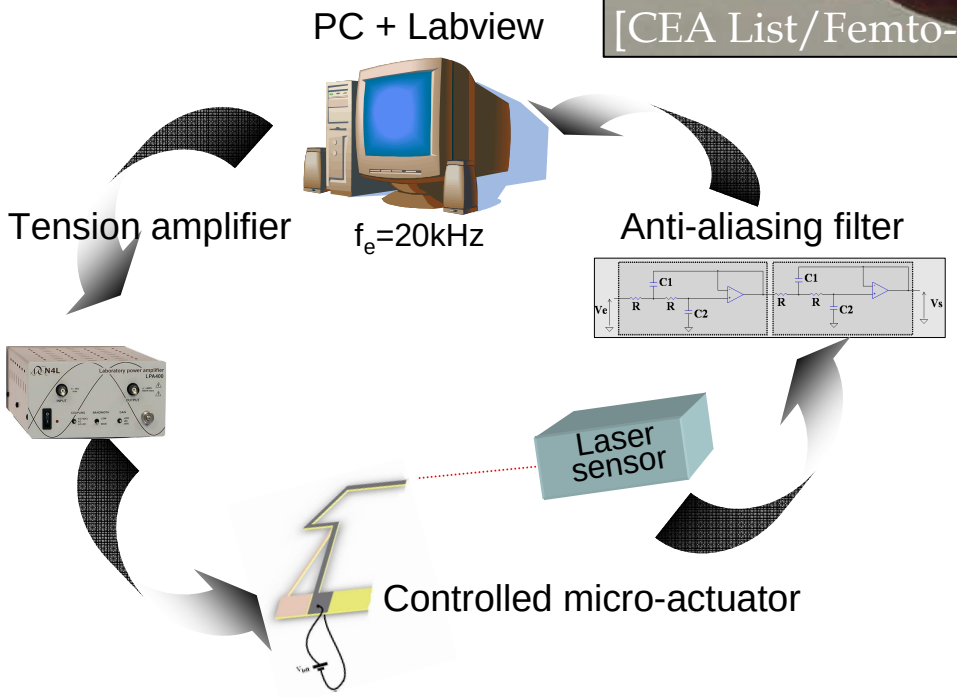
Tension Vp=±100V

δ_{free}=±10,69µm

$F_{blocking}$=840mN

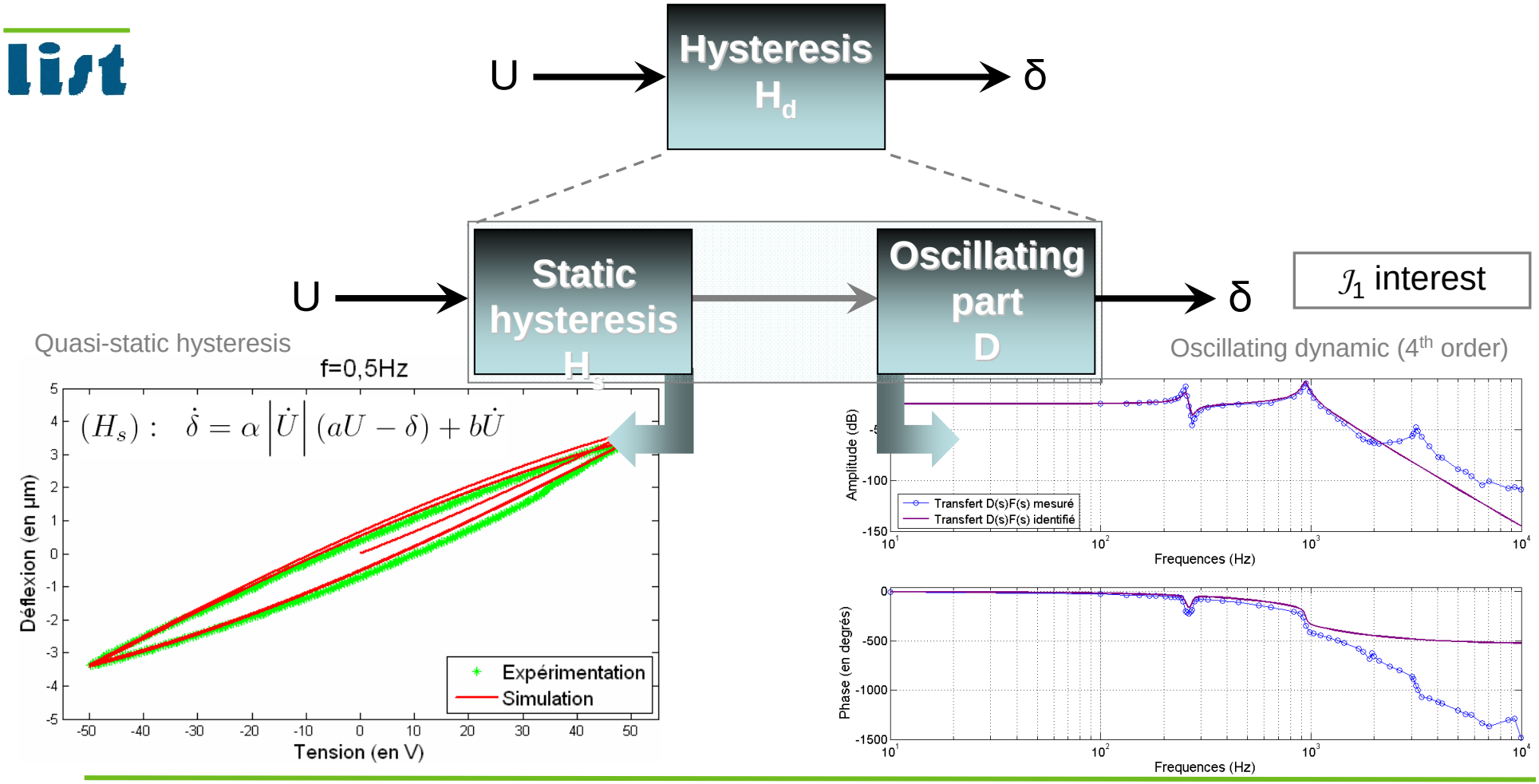






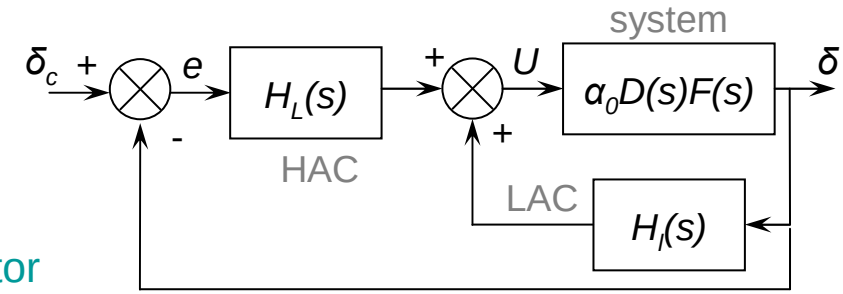
Model of the H_d hysteresis

➢ Validation of the separation principle

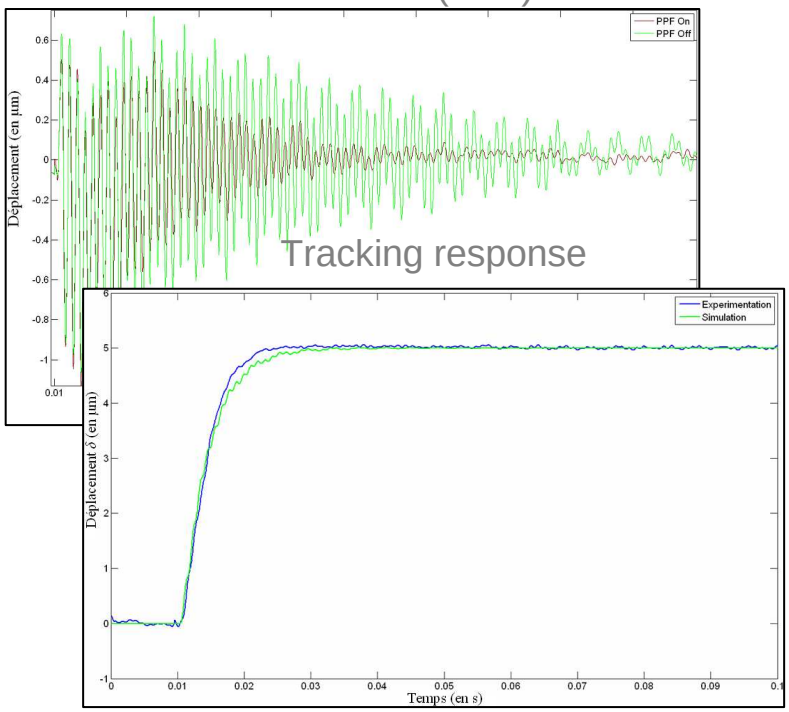


HAC/LAC control

- Double feedback loop
  - ✓ LAC corrector
    - damping of the first mode
    - *Positive Position Feedback* corrector
    - Sytnhesis using *Root Locus*
  - ✓ HAC corrector
    - tracking
    - frequency synthesis from the pre-compensated system using H_I
  - ✓ performances
    - $T_{R5\%}$=9.9ms
    - Interesting stability margins
      - M_g>16dB
      - M_φ>78°



LAC corrector (PPF)

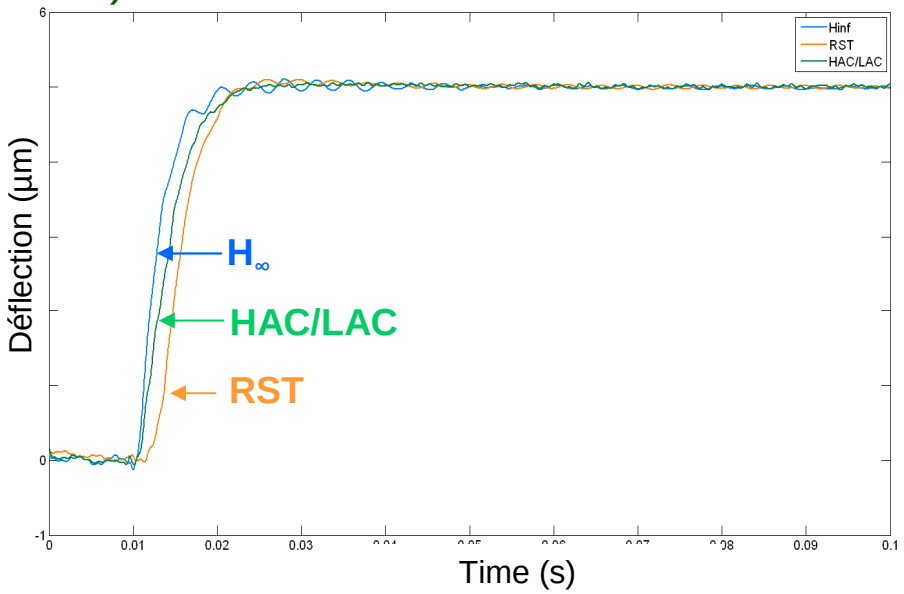


Performances comparisons

- Similar performances
  - ✓ settling time
  - ✓ stability margins

- Interest of HAC/LAC approach
  - ✓ Reduced order of corrector (order 4)
    - corrector H_∞
      order *13*
    - corrector RST
      order *9*
  - ✓ More *direct* synthesis

- Interest of proposed criteria



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Conclusion

- Developement of a new method for the optimal design
  - ✓ elementary building blocks activated by piezoelectric effect
  - ✓ Interest of the dynamic part and the modal authority control

- Optimal synthesis of a new monolithic microgripper
  - ✓ Use of our method on a simple case
  - ✓ Identification and control of the prototype
  - ✓ Several robust control techniques tested

➡ New tool of multidisciplinary optimal design taking into account simultaneously mechanical and control-oriented aspects

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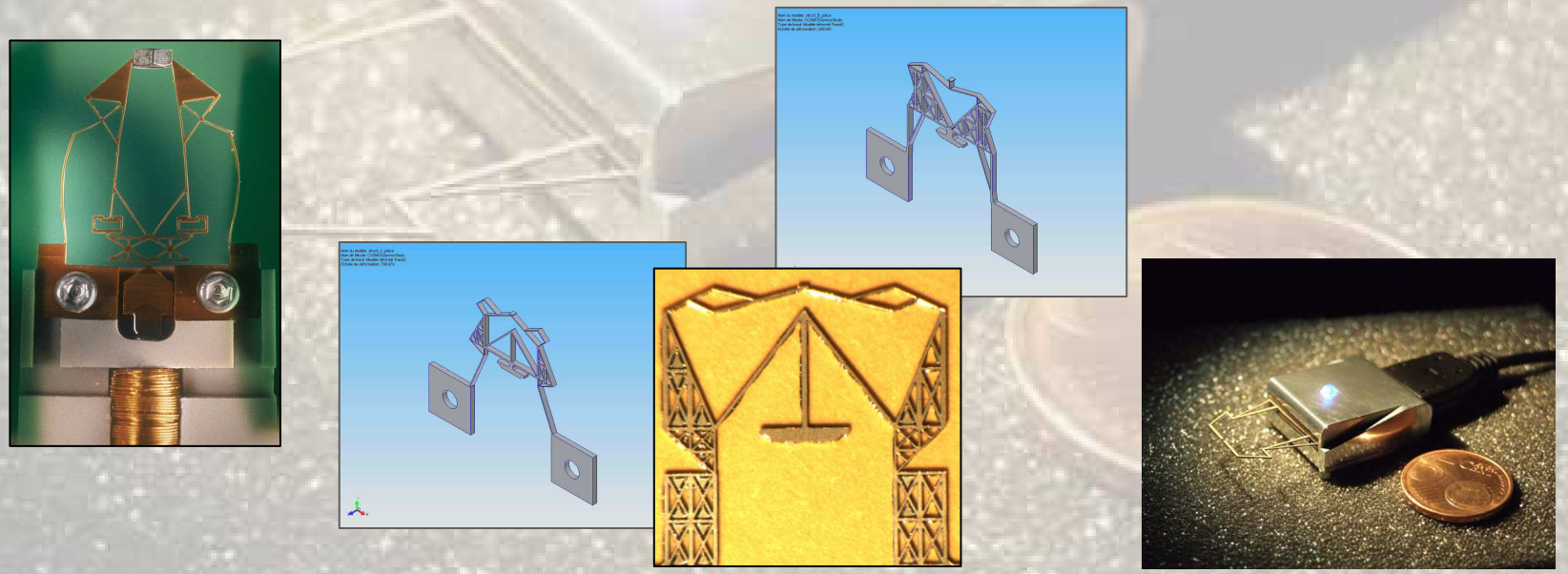
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