Task based optimal design

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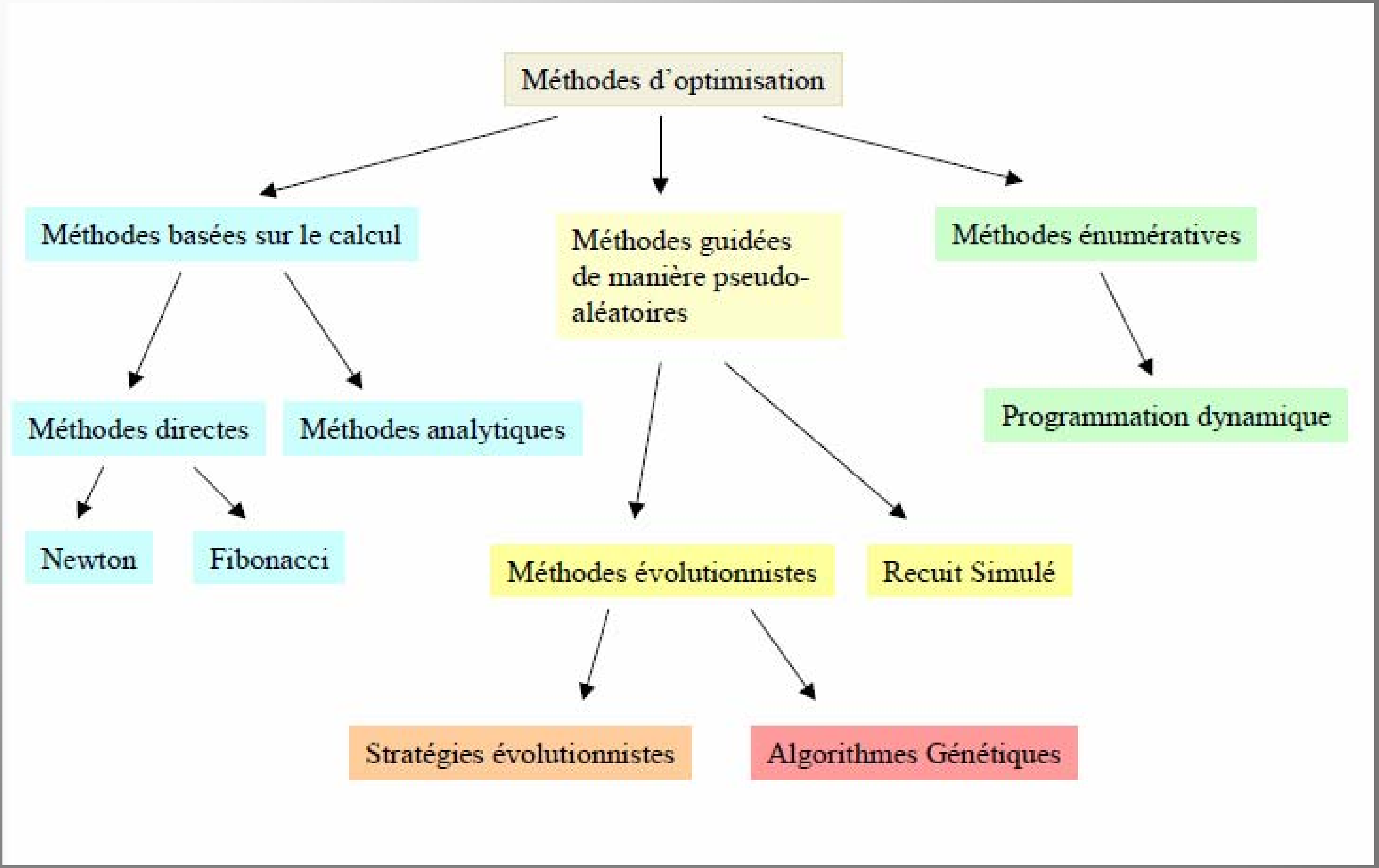
Optimization techniques

- Development of the simplex method by Dantzig in 1947 for linear programming problems
- The enunciation of the principle of optimality in 1957 by Bellman for dynamic programming problems,
- Work by Kuhn and Tucker in 1951 on the necessary and sufficient conditions for the optimal solution of programming problems laid the foundation for later research in non-linear programming.
- The contributions of Zoutendijk and Rosen to nonlinear programming during the early 1960s have been very significant.
- Work of Carroll and Fiacco and McCormick facilitated many difficult problems to be solved by using the well-known techniques of unconstrained optimization.
- Geometric programming was developed in the 1960s by Duffin, Zener, and Peterson.
- Gomory did pioneering work in integer programming, one of the most exciting and rapidly developing areas of optimization. The reason for this is that most real world applications fall under this category of problems.
- Dantzig and Charnes and Cooper developed stochastic programming techniques and solved problems by assuming design parameters to be independent and normally distributed.



Méthodes d'optimisation
Méthodes basées sur le calcul
Méthodes guidées de manière pseudo-aléatoires
Méthodes énumératives
Méthodes directes
Méthodes analytiques
Programmation dynamique
Newton
Fibonacci
Méthodes évolutionnistes
Recuit Simulé
Stratégies évolutionnistes
Algorithmes Génétiques

L. R. P.

Optimization techniques

Find the best motion regarding the quadratic criteria

$$\frac{1}{2}\begin{bmatrix}\begin{bmatrix}\dot{\boldsymbol{v}}_r\\ \ddot{\boldsymbol{q}}\end{bmatrix}\\ \boldsymbol{\tau}\\ \boldsymbol{f}_c\end{bmatrix}^{\mathrm{T}}\begin{bmatrix}Q_{\text{motion}} & 0 & 0\\ 0 & Q_{\text{joint}} & 0\\ 0 & 0 & Q_{\text{contact}}\end{bmatrix}\begin{bmatrix}\begin{bmatrix}\dot{\boldsymbol{v}}_r\\ \ddot{\boldsymbol{q}}\end{bmatrix}\\ \boldsymbol{\tau}\\ \boldsymbol{f}_c\end{bmatrix}+\begin{bmatrix}p_{\text{motion}}\\ p_{\text{joint}}\\ p_{\text{contact}}\end{bmatrix}^{\mathrm{T}}\begin{bmatrix}\begin{bmatrix}\dot{\boldsymbol{v}}_r\\ \ddot{\boldsymbol{q}}\end{bmatrix}\\ \boldsymbol{\tau}\\ \boldsymbol{f}_c\end{bmatrix}$$

Under the constraints

$$\begin{bmatrix}M & -S & J_c^{\mathrm{T}}\\ J_c & 0 & 0\end{bmatrix}\begin{bmatrix}\begin{bmatrix}\dot{\boldsymbol{v}}_r\\ \ddot{\boldsymbol{q}}\end{bmatrix}\\ \boldsymbol{\tau}\\ \boldsymbol{f}_c\end{bmatrix}=\begin{bmatrix}-\boldsymbol{n}+M\boldsymbol{g}\\ -\dot{J}_c\begin{bmatrix}\boldsymbol{v}_r\\ \dot{\boldsymbol{q}}\end{bmatrix}\end{bmatrix}$$

$$\begin{bmatrix}0 & I & 0\\ 0 & -I & 0\\ 0 & 0 & A\end{bmatrix}\begin{bmatrix}\begin{bmatrix}\dot{\boldsymbol{v}}_r\\ \ddot{\boldsymbol{q}}\end{bmatrix}\\ \boldsymbol{\tau}\\ \boldsymbol{f}_c\end{bmatrix}\leq\begin{bmatrix}\boldsymbol{\tau}_{\max}\\ -\boldsymbol{\tau}_{\min}\\ 0\end{bmatrix}$$

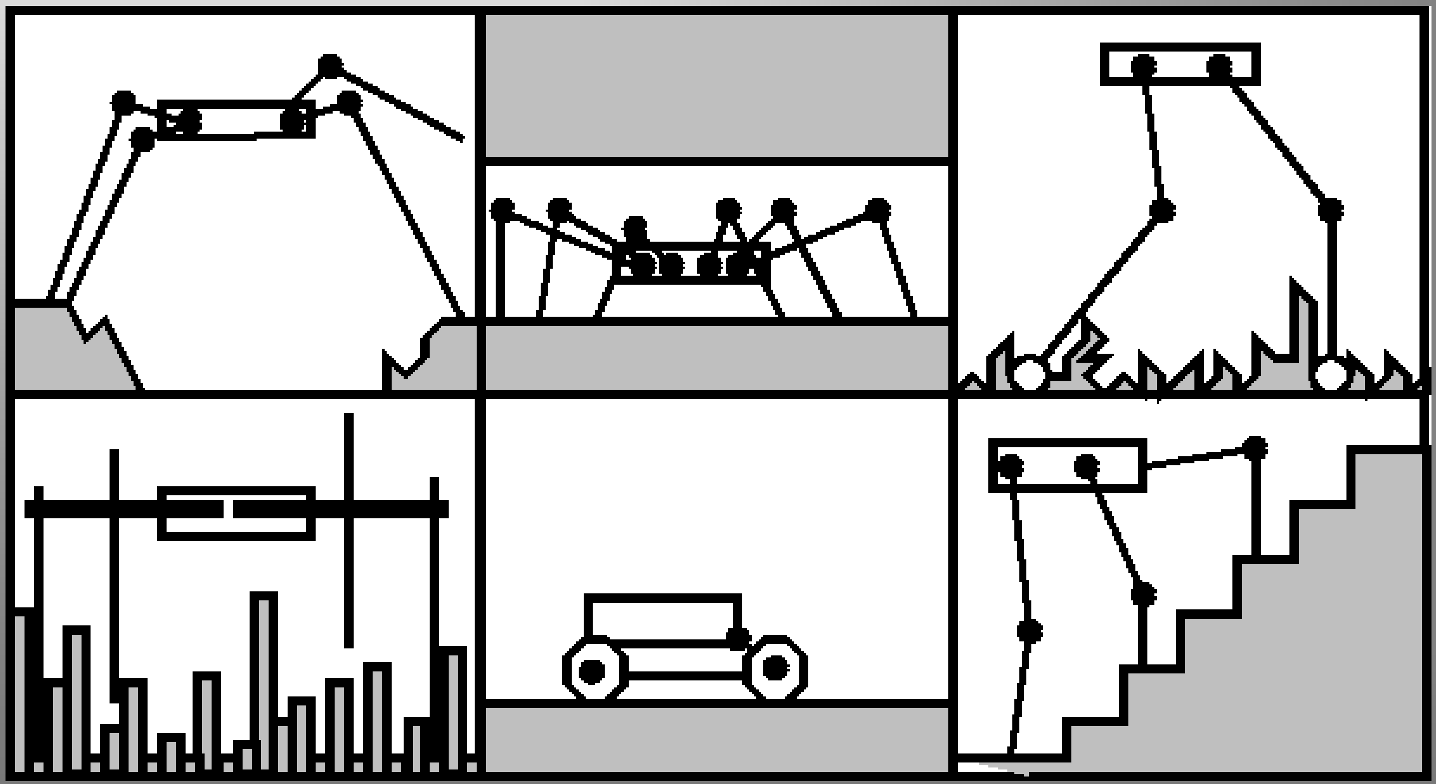
Optimization techniques

Mobile robot design
Task specification example

Task-based topological optimization

Problem statement :

Finding the best feasable configuration from the current configuration of the system for a given task is a combinatorial optimization problem.



Comments on the design issues

L. R. P.

To create (i.e. to design) artefacts that are capable of carrying out the tasks,

☞ Quantitative descriptions of robot performances are key issues

☞ In robotics, the performance measure depends on the nature of the system and the nature of the task.
A performance measure assigns a numerical value (the cost) to a system and a particular manner (control & programming) of executing this task.

☞ Finding the "best" system and the "best" way to execute the task can be translated into an optimization problem.

☞ The formulation of appropriate objective functions requires to take into account task variability (MO).

Analysis of the design problems

- Task complexity (complex trajectories, force/motion constraints, highly constraint environment)
- Specificity of the surgical practices
- Creative design
- Simultaneous mechanical, actuation, and control design

What makes EAs so valuable

☞ Some advantages of evolutionary design methods

- problems specification:

  complex tasks (specification)
  task diversity (adaptation)

- objective functions:

  irregularities, non-valuated parameters,
  multi-criteria , non explicit constraints

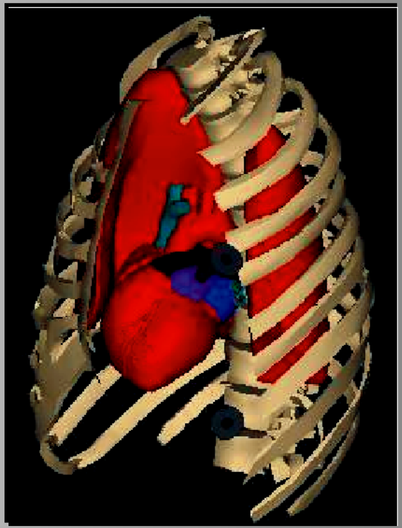
- search:

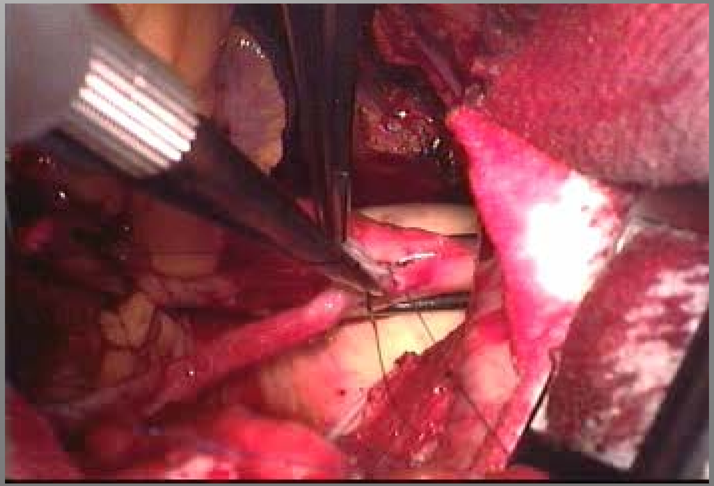
global, parallel, huge search spaces, difficult constraints, family of solutions, can be made adaptive

- drawbacks : needs a great deal of time and expertise

Illustration of Microsurgical systems

Instrument for
Minimally Invasive Coronary Artery Bypass Grafting





- Complex motion of suture with a circular needle
- Insertion constraints and obstacle avoidance
- High force transmission capacities (thread)
- Interaction force control
- Miniaturized technologies

Illustration of Microsurgical systems

Micro-Active Endoscope & Colonoscope

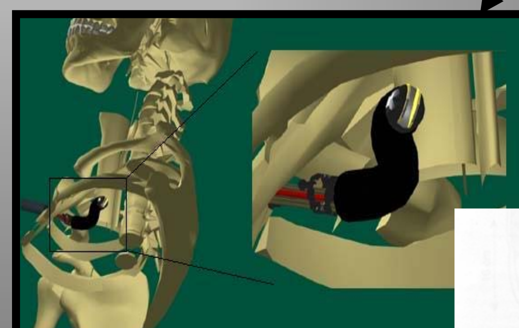
- Controllable tight bends in the 3D space of the endoscope

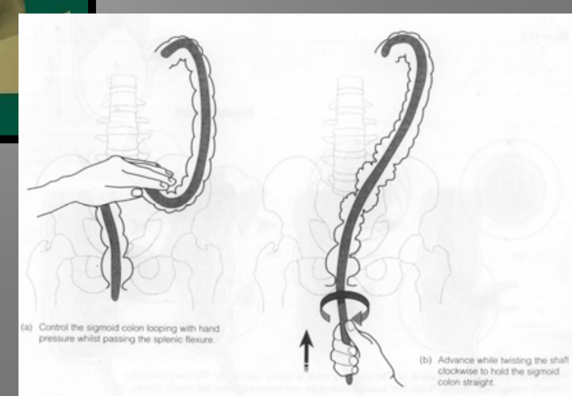
- Adaptation of the local curvature to the interior geometry in reaction to interactions

- Sterilization
  (140° during 20 minutes)

- Scalable technologies

- Variable field optical system





Active endoscope

Example of proposed design

Distal portion of an active endoscope

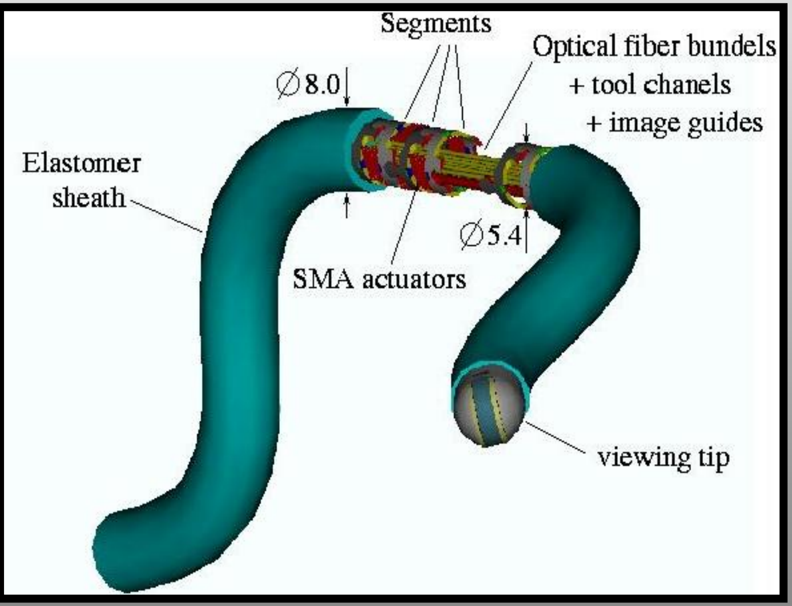
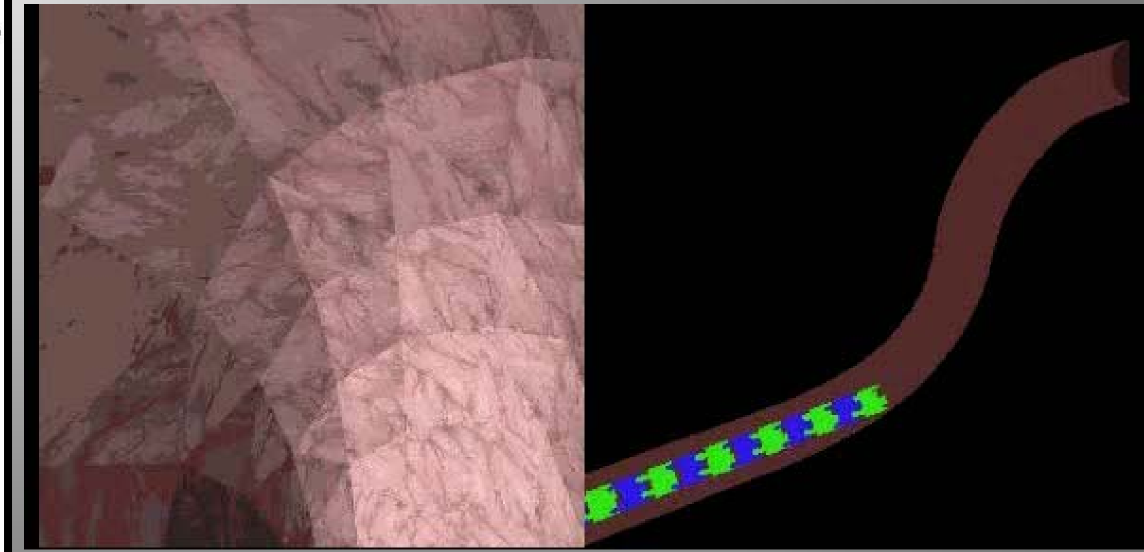


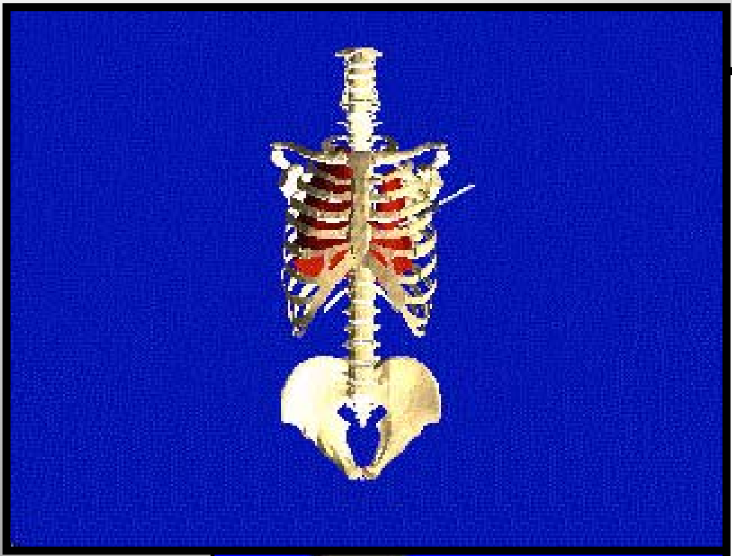
Illustration of a behaviour in colonscopy

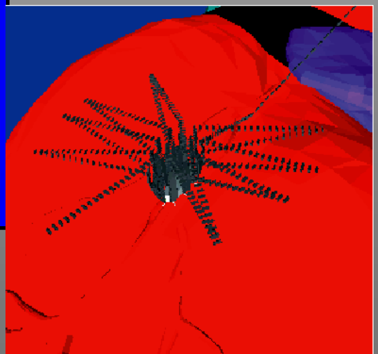


Micro-suturing instrument

Example of proposed design

Dextrous instrument for thoracic minimally invasive surgery

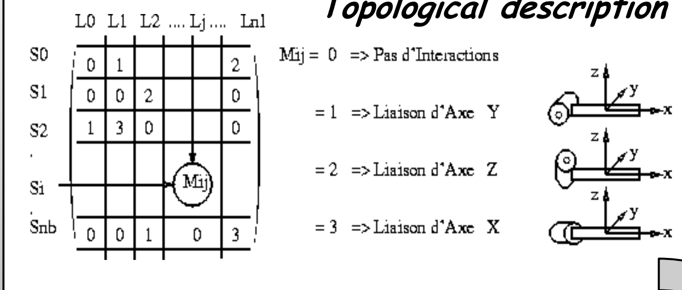




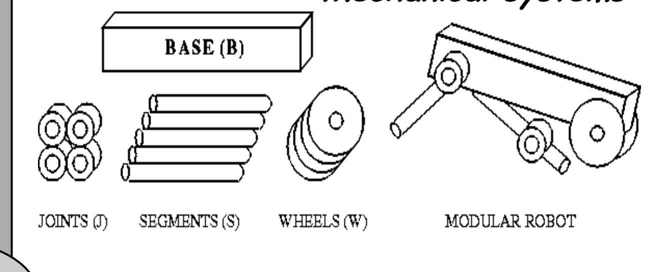
Bypass Grafting trajectory

Design approach

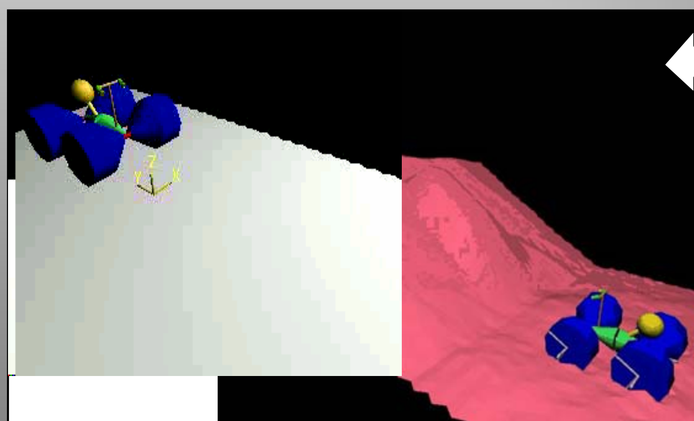
☞ Task-oriented design of systems and their associated control



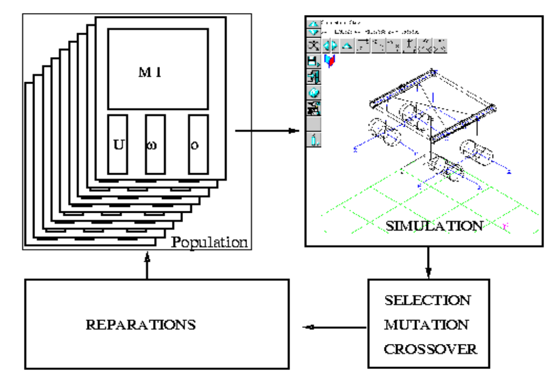
Topological description



Mechanical systems



Evaluation



Associated Control

Task specification
Data acquisition

Illustrations through some research developments

Thanks to …..

Vincent Desars (PhD)

Damien Salle (PhD)

Christopher Khul (PhD)

Paul Bernardoni (PhD)

Frédéric Chapelle (PhD)

Sébastien Rubrecht (PhD)

1.EVOLUTIONARY OPTIMIZATION OF MECHANICAL AND CONTROL DESIGN

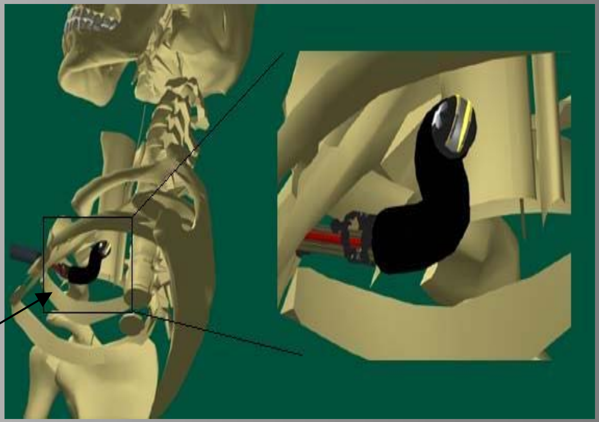
Considered problem

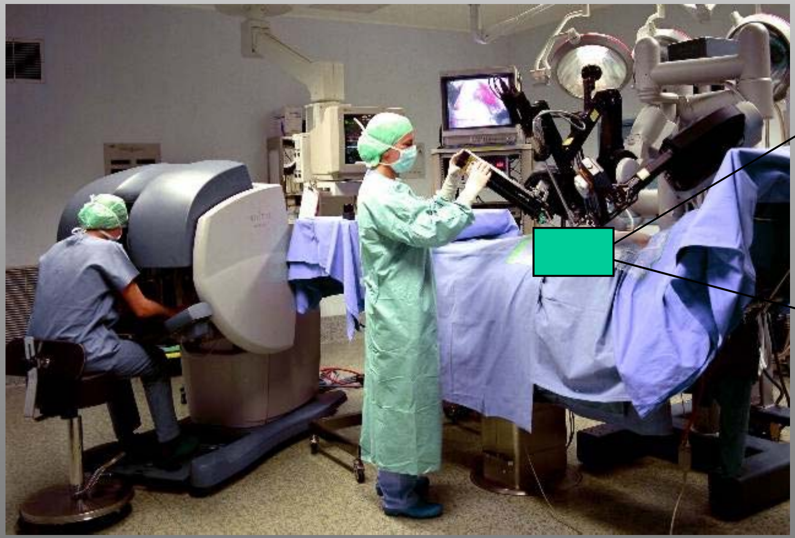
☞ *Design of the distal portion of endoscopic systems*

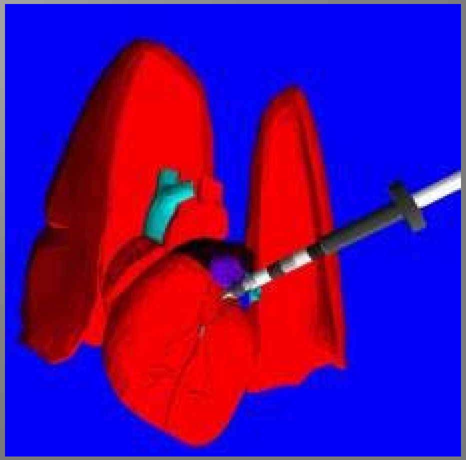
System requirements

1) Controllable tight bends in the 3D space

2) Adaptation of the local curvature to the interior geometry in reaction to interactions

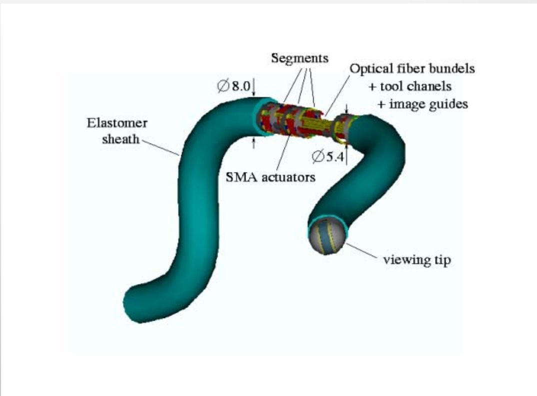


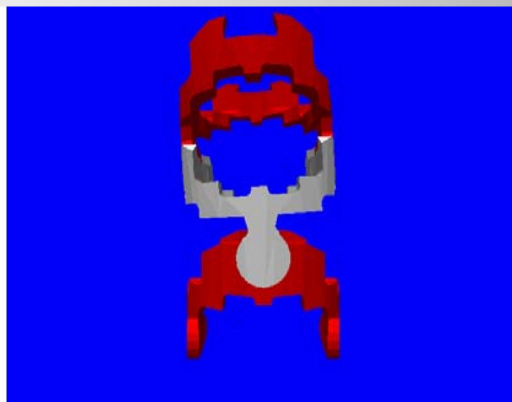


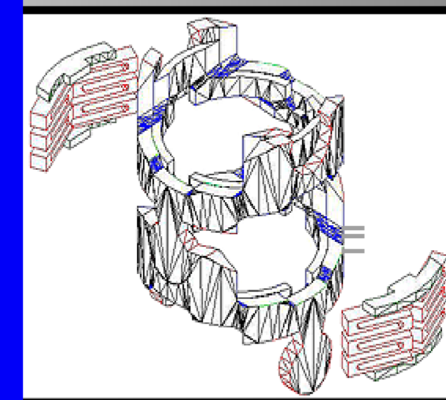


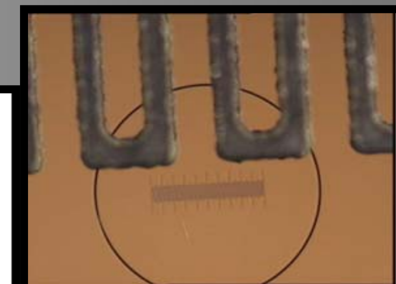
System design

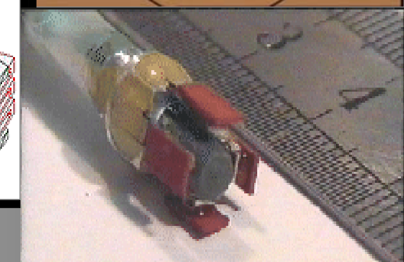
- *Endoscope structure*



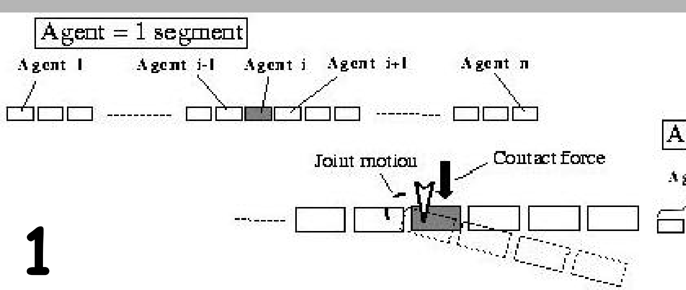




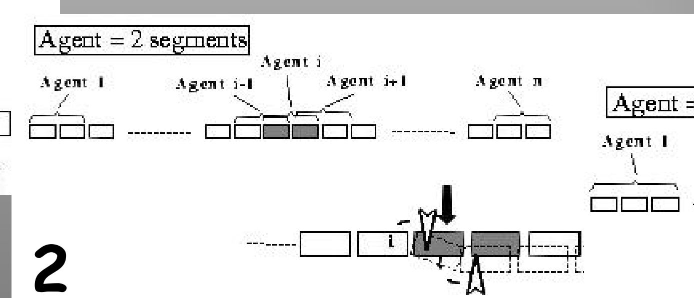




- *Reactive control strategies*



1



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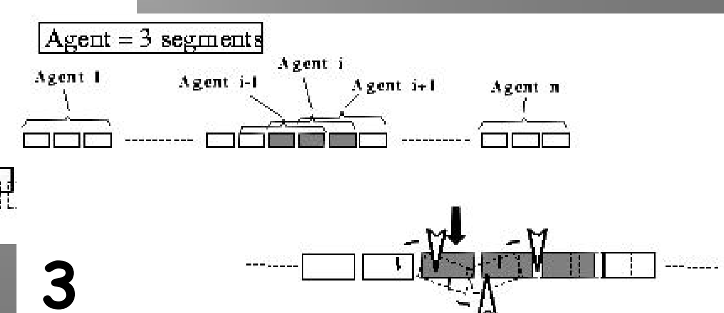
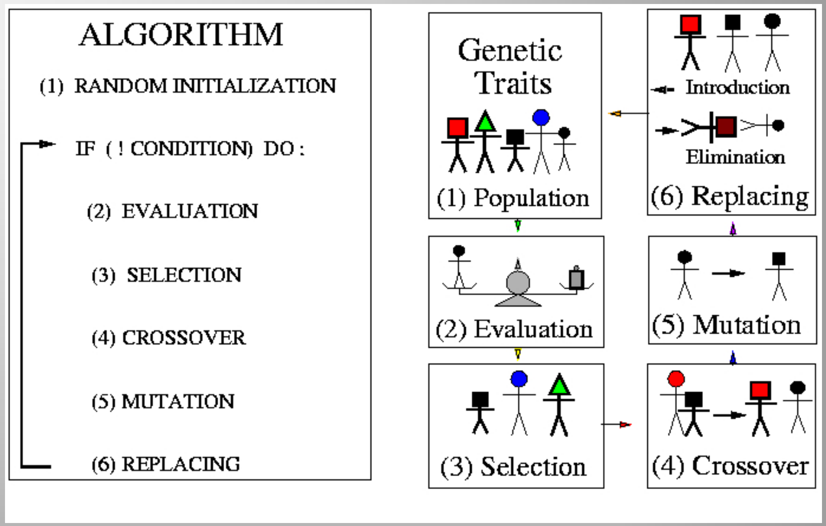


3

4, 5, 6, …

Principles of the design process

☞ *Basic principles of Evolutionary Algorithms*



☞ *Some advantages of evolutionary design methods*

- **problems** : adapted to complex tasks (specification) and task diversity (adaptation)
- **objective functions** : irregularities, non-valuated parameters, multi-criteria
- **search** : global, huge search spaces, difficult constraints, family of solutions

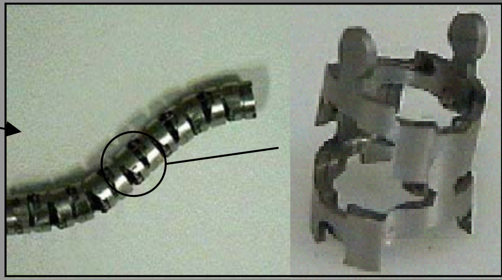
Genetic Algorithm design

☞ *Encoding*

Genome composed of a string of real numbers with variable size

Control strategy	Length of 1st module	Lenght 2nd module	Joint orientation between modules	……. …….	…… ……

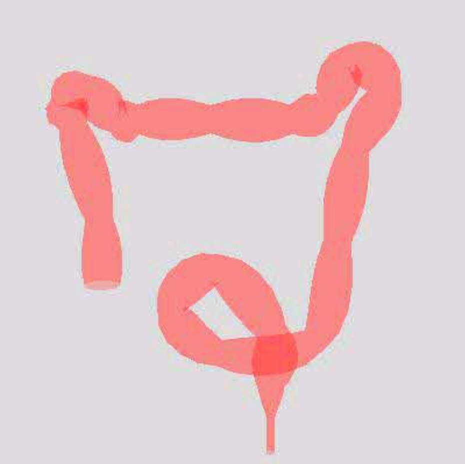
2n genes



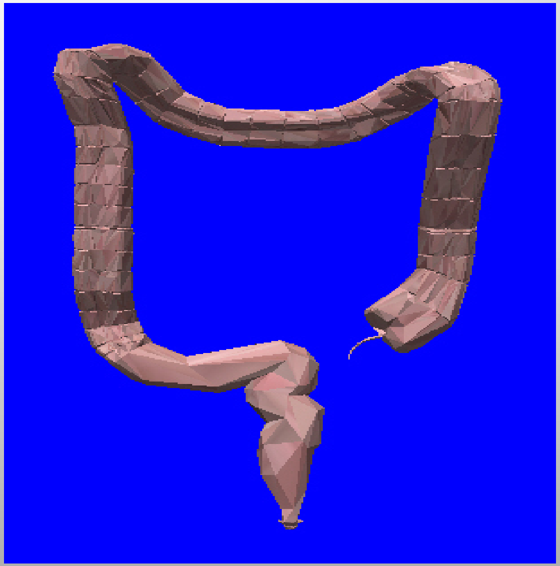
☞ *Genetic operator*

- arithmetic crossover : $E_1 = \alpha P_1 + (1- \alpha) P_2$
  $E_2 = \alpha P_2 + (1- \alpha) P_1$
- mutation (Gaussian disturbance) : $X'_i = X_i + N(0,\sigma)$
- linear scaling on the fitness

Application to colonoscopy



☞ *Function description*



☞ *Task evaluation*

For the particular application, a fitness function is :

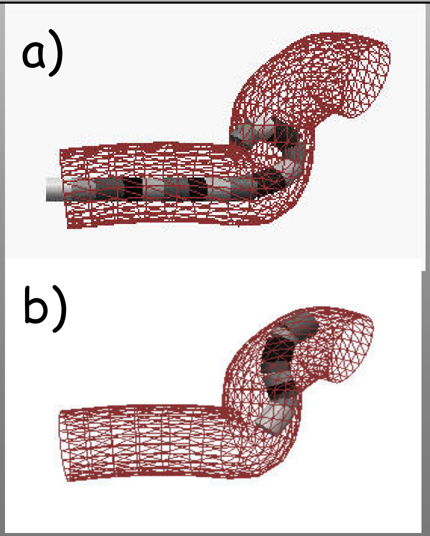
Fitness : a/(Σ Rotations) + b/(Σ Contacts) + (Penetrating Distance)

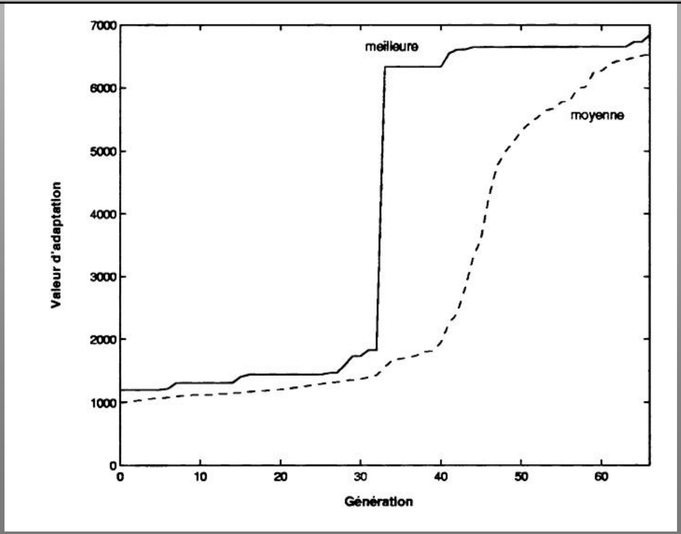
Application to colonoscopy

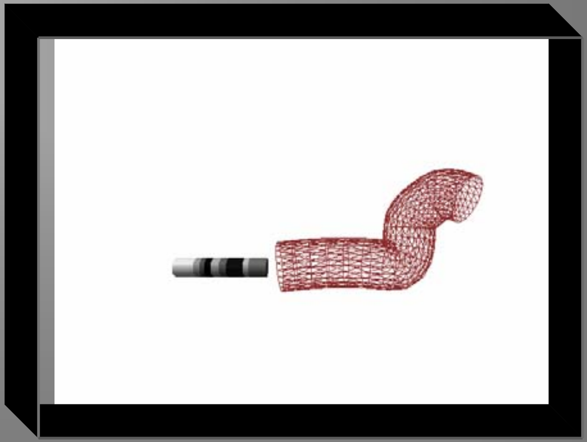
☞ *GA design*

GA : Steady state
Percentage of replacement : 50%
Population size : 50
Max. number of generations : 70
Crossover probability : 0.9
Mutation probability : 0.01
Fitness scaling : Linear

☞ *Exemple of results :*







2.Synthesis of evaluation functions

Synthesis of evaluation functions

☞ *Previous works*

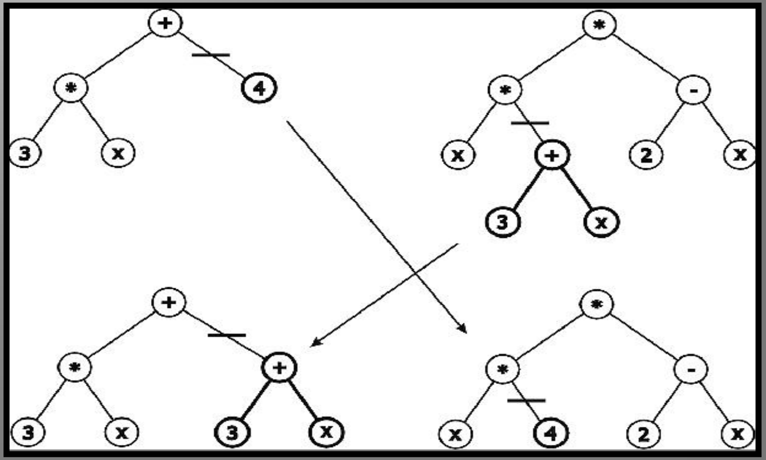
o ***F. Chapelle, Ph. Bidaud*** *– A closed form for inverse kinematics approximation of general 6R manipulators using genetic programming – in Proc. IEEE Int. Conf. on Robotics and Automation – Seoul 2001*

☞ *Analytical functions approximating simulations or evaluation functions based on Evolutionary symbolic regression using genetic programming*

o **Evolutionary search to computer programs encoded as tree-structures**

o **Nodes can be functions or terminals, functions may require several arguments and terminals can be numbers or variables**

o **Illustration of the crossover process**



Synthesis of evaluation functions

☞ *Configuration parameters of the evolutionary symbolic regression*

Population size : 5000
Max. number of generations : 70
Selection : Tournament
Crossover Probability : 100
Fitness scaling : Linear
Creation type : Ramped half and half
Replacement : Steady state
Max depth for creation : 6
Max depth for crossover : 17

☞ *Set of functions and terminals*

Functions	**Terminals**
pow,sqrt,cos,sin,tan,arcos,	*100,10,1,PI*
arcsin,arctan2,ln,exp,+,-,,/*	gen_{1}, ..., gen_{36}

☞ *Learning base*

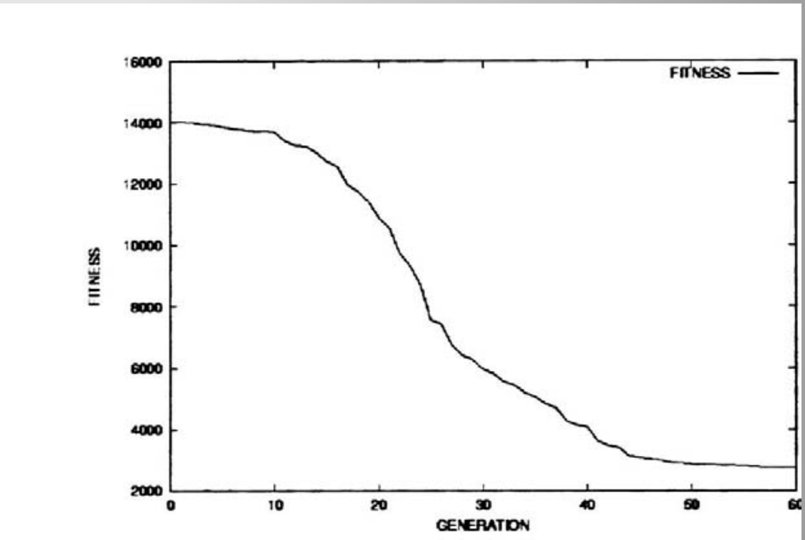
About 2000 characteristic points chosen randomly among all possible genomes

Synthesis of evaluation functions

☞ *Results :*

- ***36000 times faster than the "real" evaluation***

- ***good solutions are found after only 40 generations***



- ***substitution of the simulation by the best approximated evaluation function shows a good preservation of the main features in the solutions***

Synthesis of evaluation functions

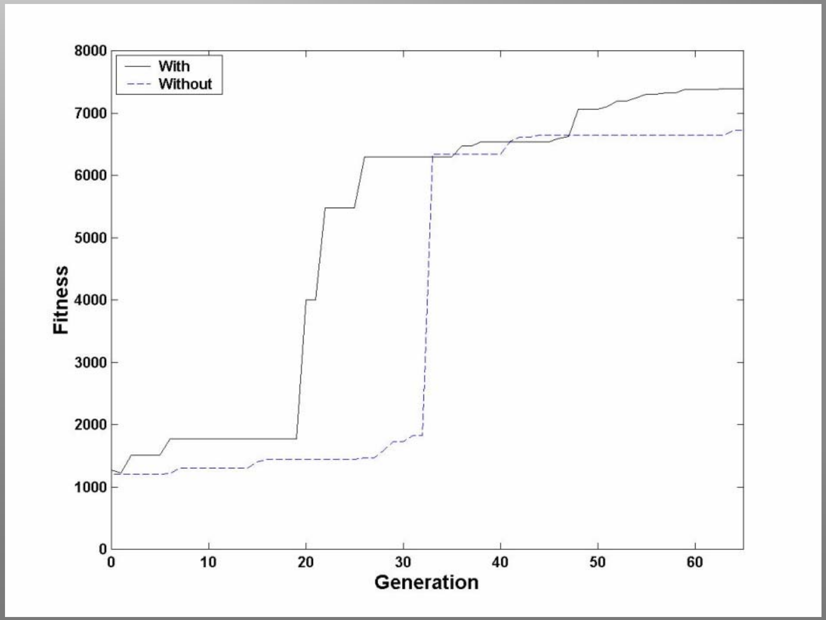
☞ *Results :*

o **some features observed in solutions:**

- the number of modules is minimum
- the length of modules close to the distal end are small.
- the best control strategy is the one which reduces risk of winding,

o **robustness of the "pseudo-fitness" function:**

Evolution with and without insertion of a pre-evaluated individual into the initial population

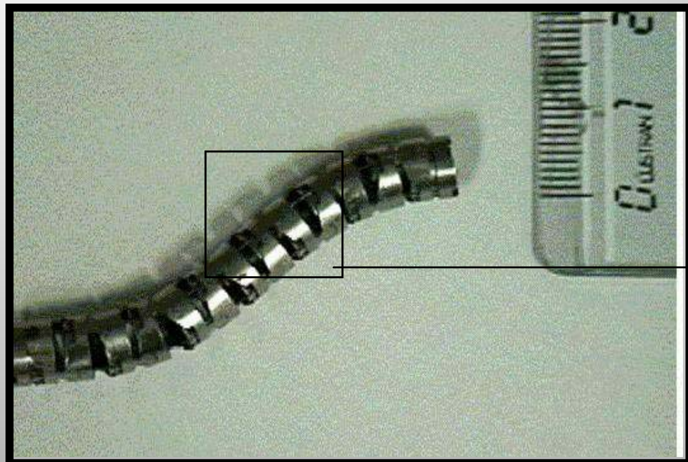


3. Design and Control of SMA actuators

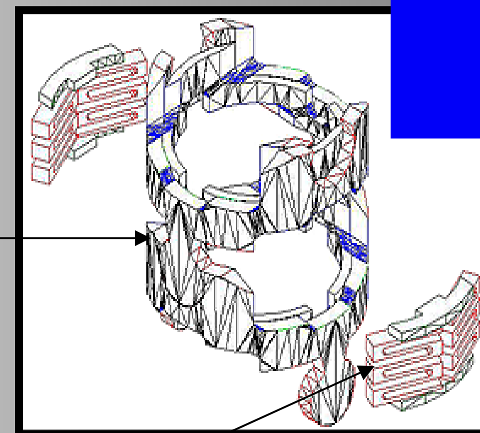
L. R. P.

Design and Control of SMA actuators

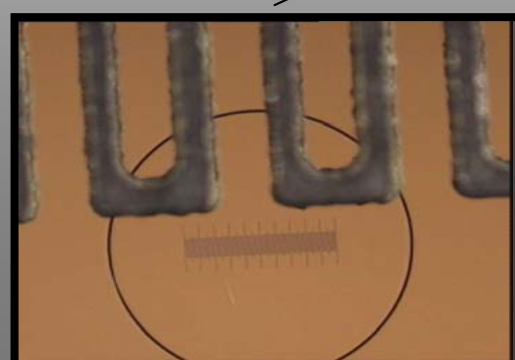
Antagonist SMA actuators



Active endoscope



Antagonist SMA



Spring like actuators

Design of SMA antagonist actuators

Antagonist SMA actuators

Performances of micro-actuators :

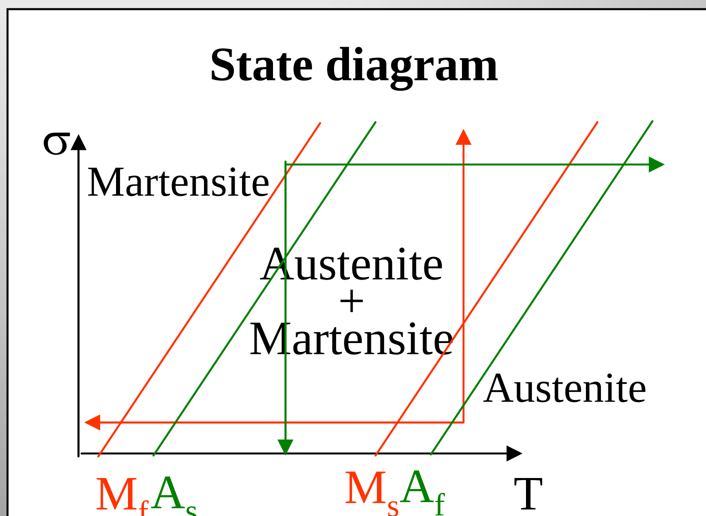
Relative Comparisons - Ten Actuator Methods

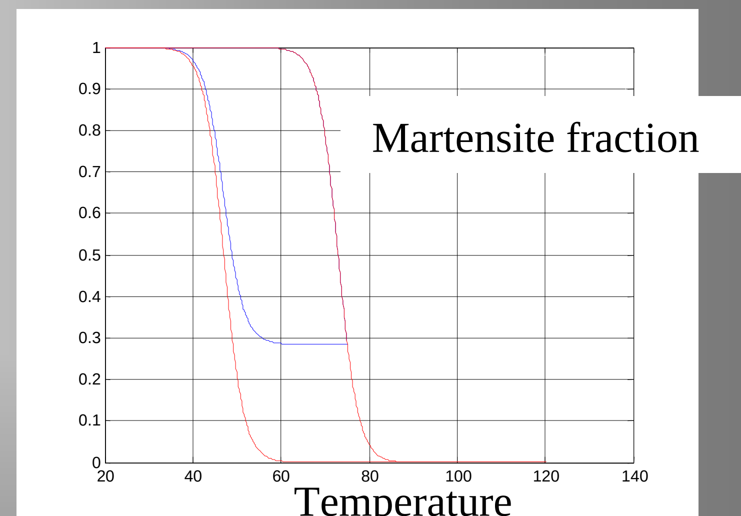
Method	Efficiency	Speed	Power Density
1 Electromagnetic	high	fast	high
2 Electrostatic	very high	fast	low
3 Thermomechanical	very high	medium	medium
4 Phase Change	very high	medium	high
5 Piezoelectric	very high	fast	high
6 Shape Memory	low	medium	very high
7 Magnetostrictive	medium	fast	very high
8 Electrorheological	medium	medium	medium
9 Electrohydrodynamic	medium	medium	low
10 Diamagnetism	high	fast	high

Design of SMA antagonist actuators

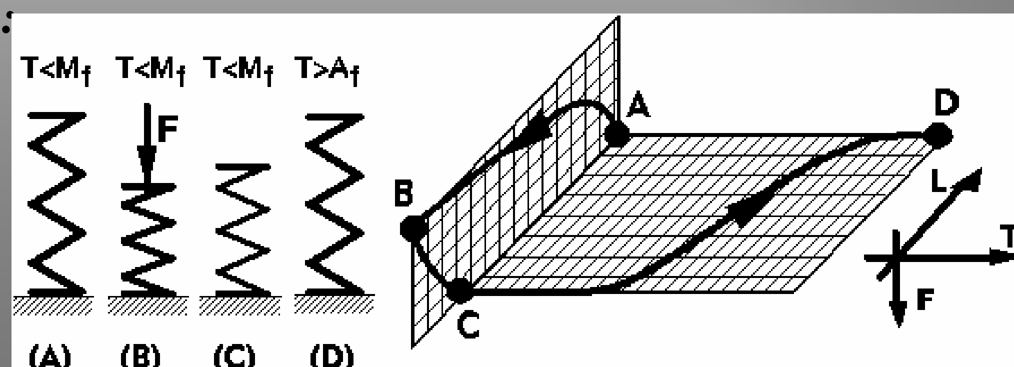
Antagonist SMA actuators

Phase transition in SMA :





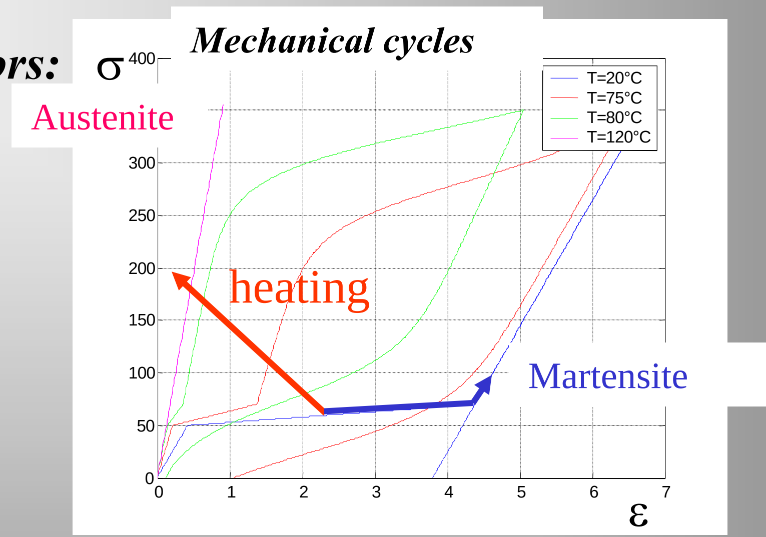
One-way memory effect :



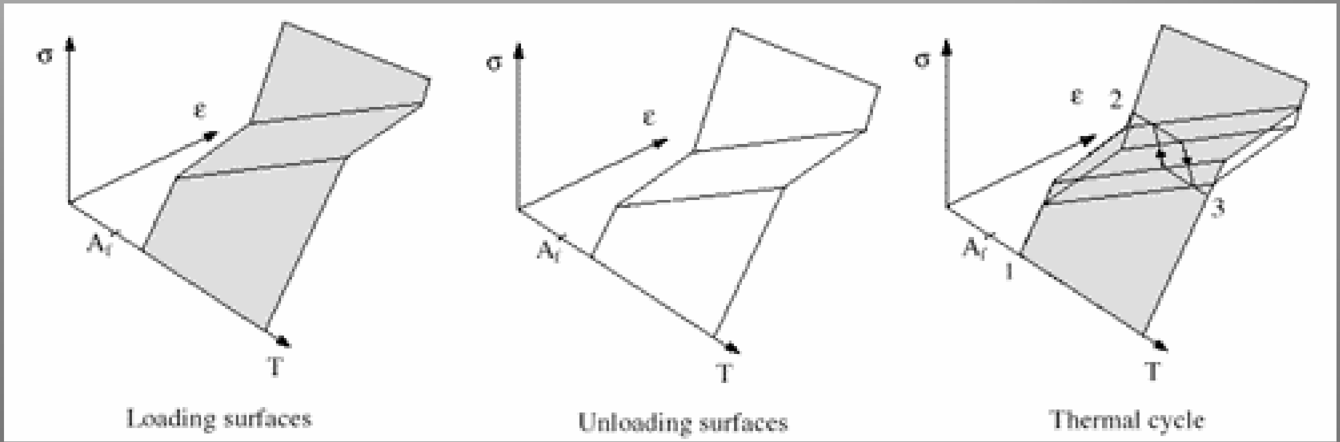
Design of SMA antagonist actuators

Antagonist SMA actuators

Antagonist SMA actuators:

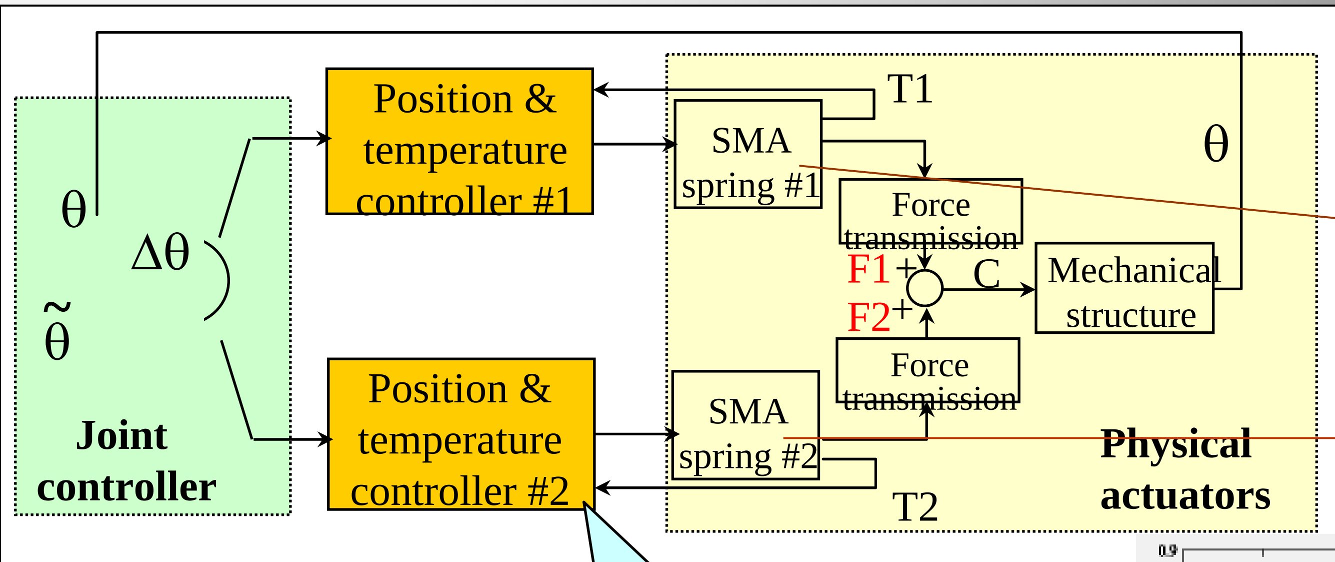


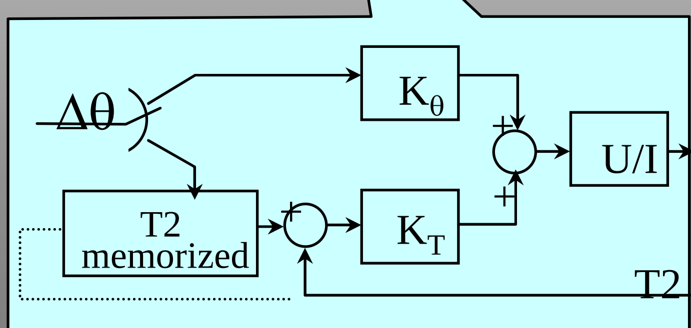
Thermomechanical behaviour of SMA :

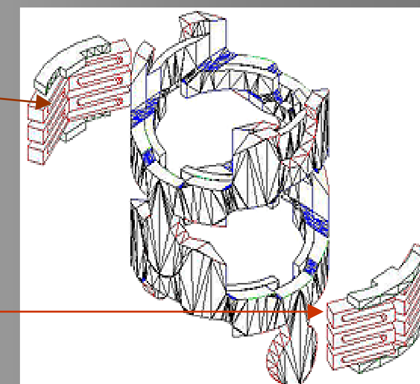


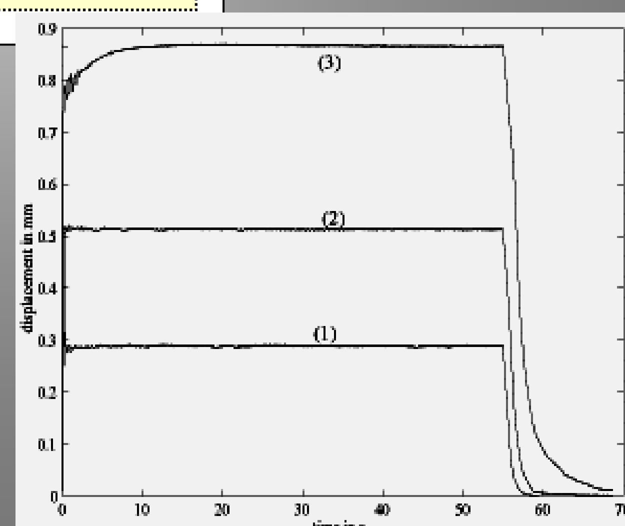
Active endoscope

Control of antagonist SMA actuators







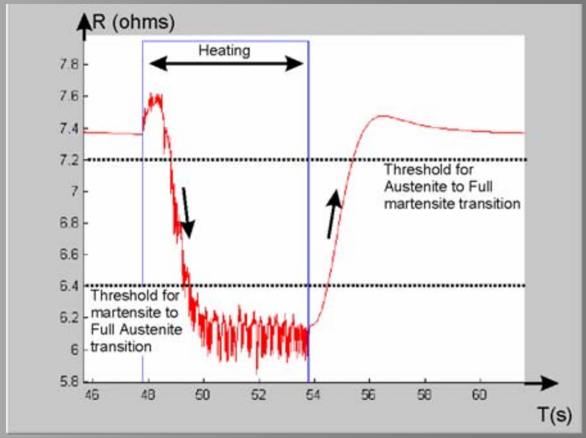


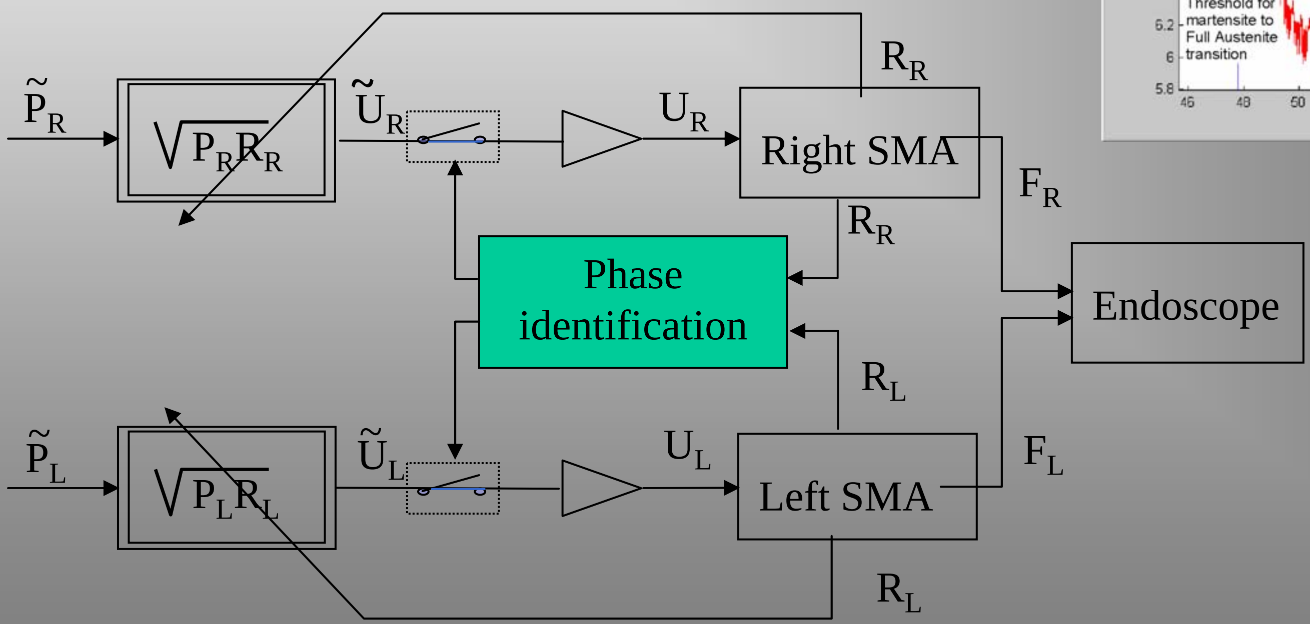
Step response

Active endoscope

Control of antagonist SMA actuators

. Phase identification through electrical resistance estimation





4. Sumultaneous mechanical and control design

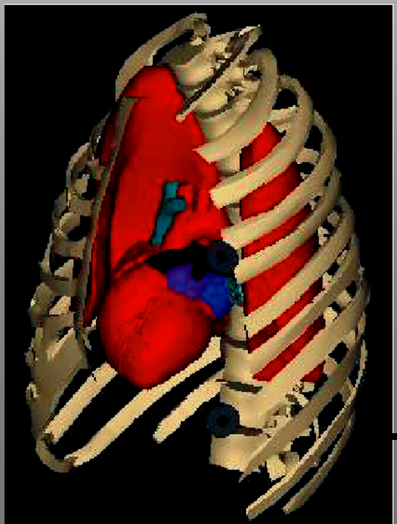
Considered problem

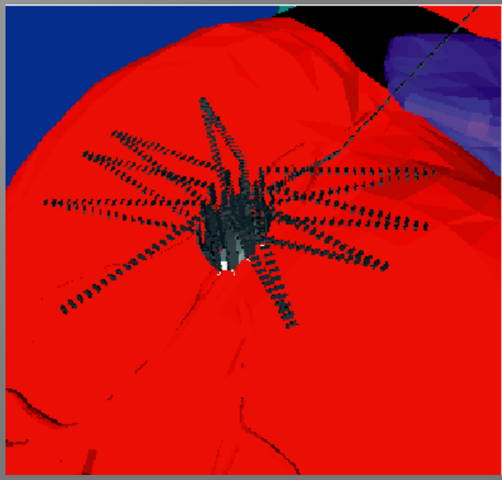
☞ *Design of dextrous instruments for heart surgery*

System requirements

1) Replication of open-air surgical gesture

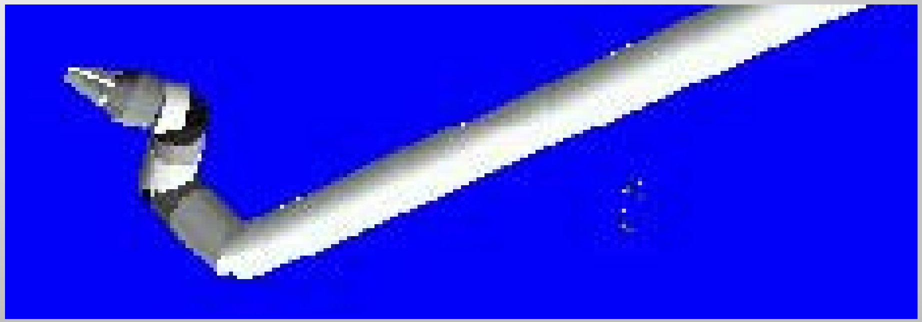
2) Adapted to minimally invasive surgery

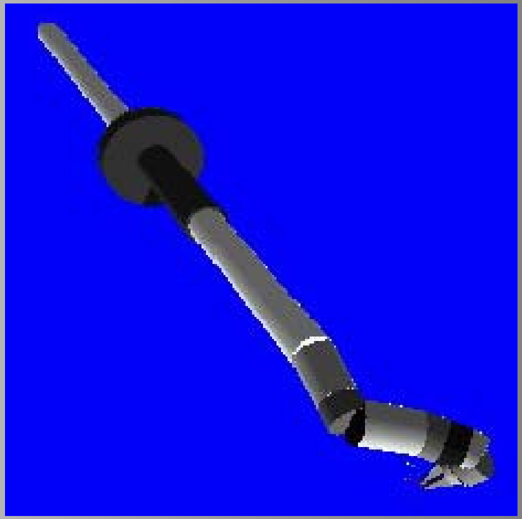




System design

☞ *Endoscope structure :*





Parameters : **Number of module,Length of modules, Rotoid joint direction**

☞ *Control strategies :*

Inverse Kinematics with redundancy optimisation:

$$dq = J^{+}\, dX + (I - J^{+}J)\, \nabla F$$

Application to Coronary Artery Bypass Grafting

☞ *Task description :*

- *Trajectory tracking*
- *Manipulability*
- *Generalized forces*
- *Distance to obstacles*
- *etc …*

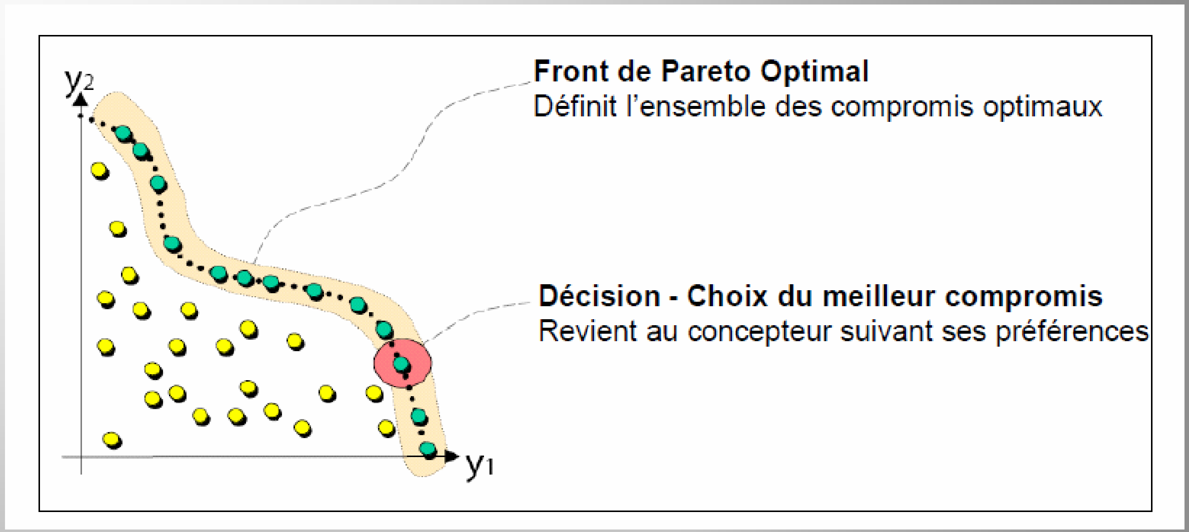
☞ *Evaluation :*

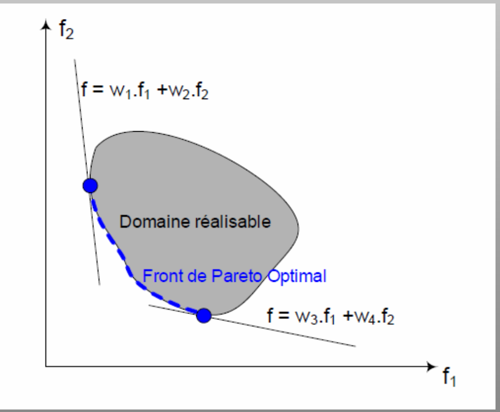
- **Single Objective**
  - **Score is a linear combination of each objective score**
  - **Result = One Instrument, optimal for the set of oefficients**
- **Multi-objective:**
  - **3 objectives: precision in the gesture, manipulability, length**

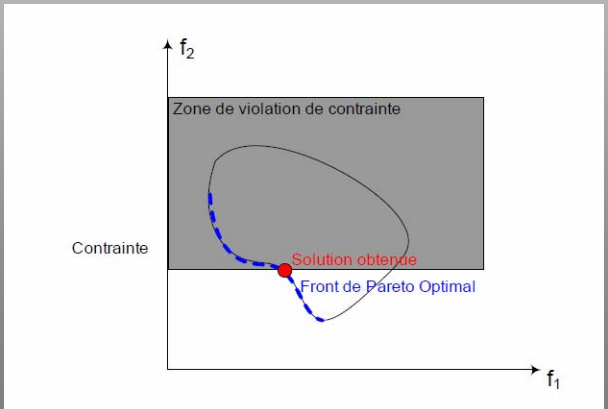
  (the multi-objective optimization is based on the Non-Dominated Sorting Genetic Algorithm)
  - **Results are Pareto front (surface) of the optimal solutions**

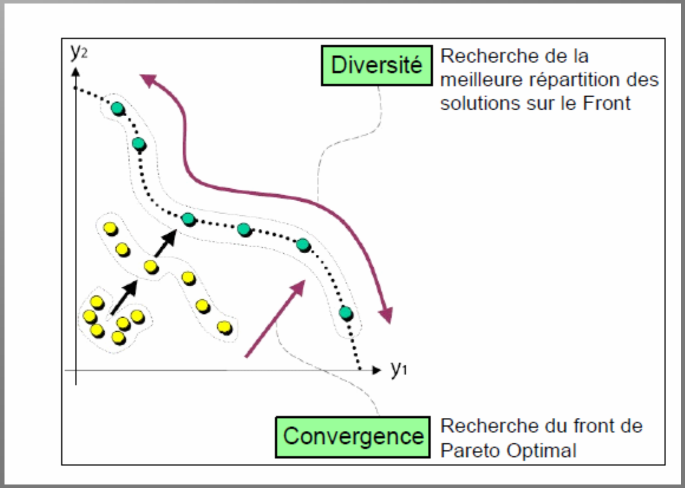
convergence to the Pareto optimal front (Veldhuizen and Lamont 1998; Rudolph 1998)

Pareto front



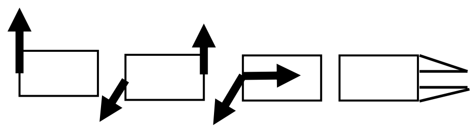






Implementation

Input: Topology + Modules



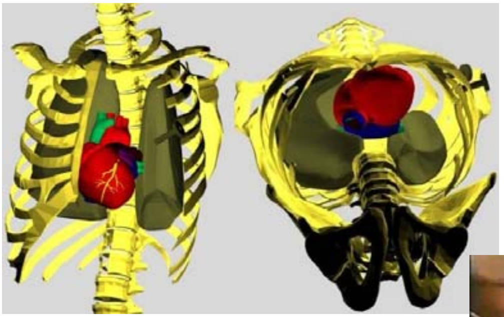
<Type1,Length1 >
<Type2,Length2 >
<Type3,Length3 >
<Gripper>

Maximum Speed

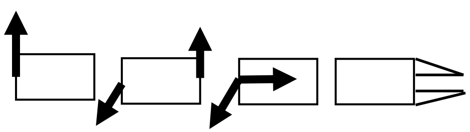
Maximum Torque

Joint range

Task specification



Outputs



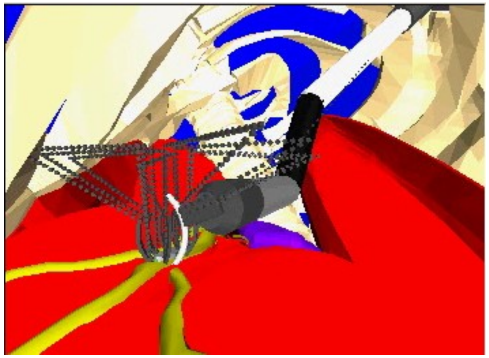
Path following capabilities

Manipulability

Maximum Joint Torque

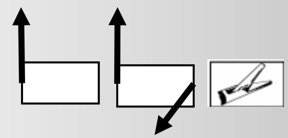
Minimum Distance to organs

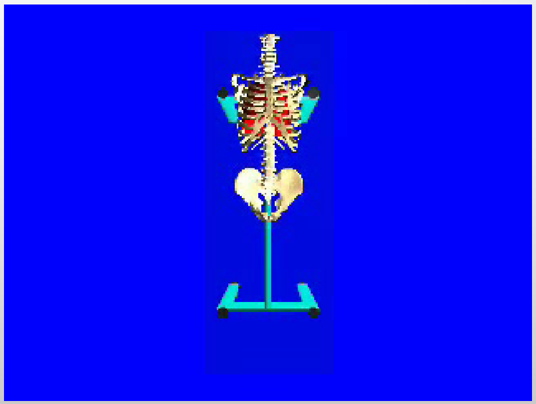
Control algorithm



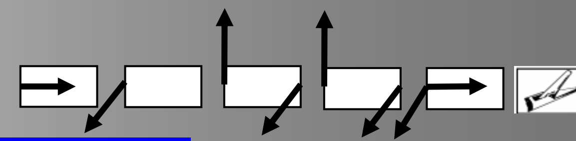
Result

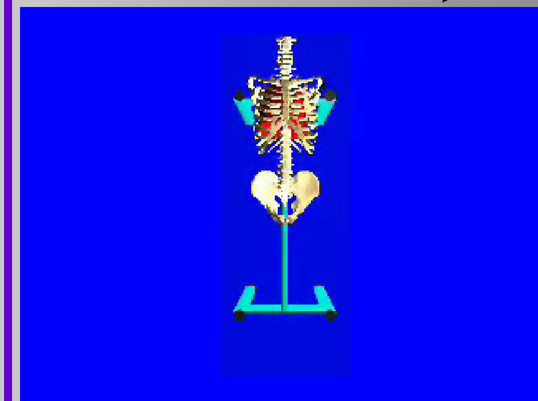
Instrument 1



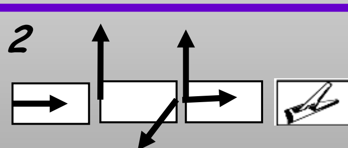


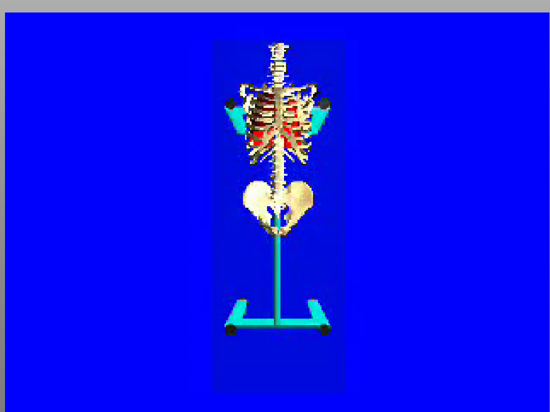
Trajectory= 2050;
Distance= 0.9;
Manip= 30722 ;
Torque= 11.7



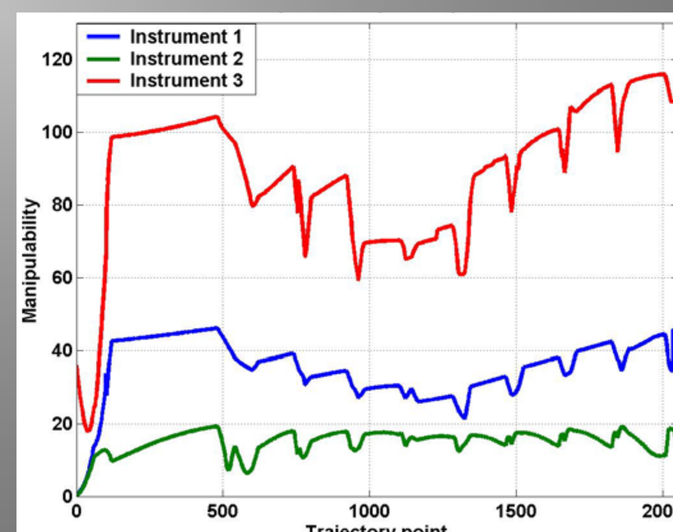


Instrument 2

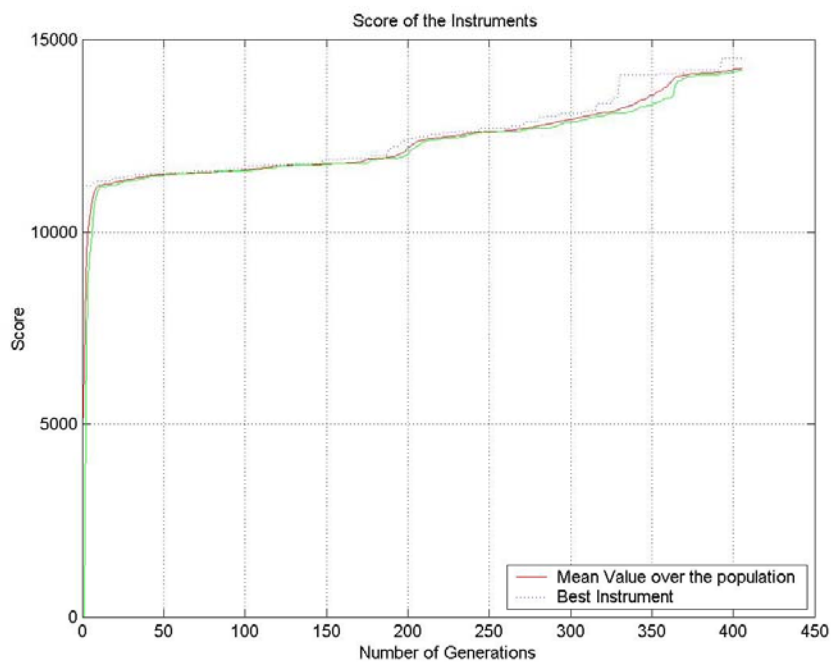




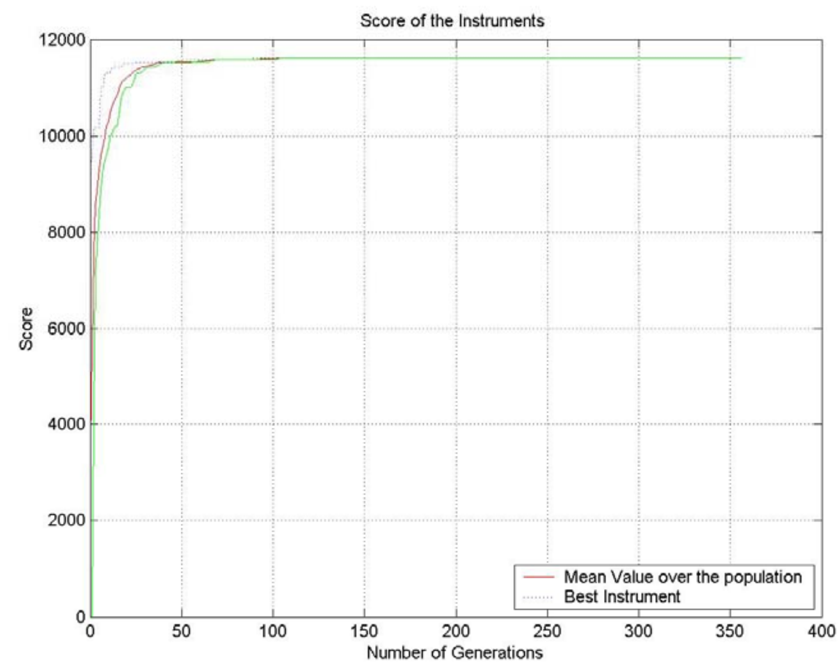
Trajectory=2050;
Distance=9.86;
Manip= 71496;
Torque= 29.45



Results for single objective optimisation



Higher coeff. : manipulability

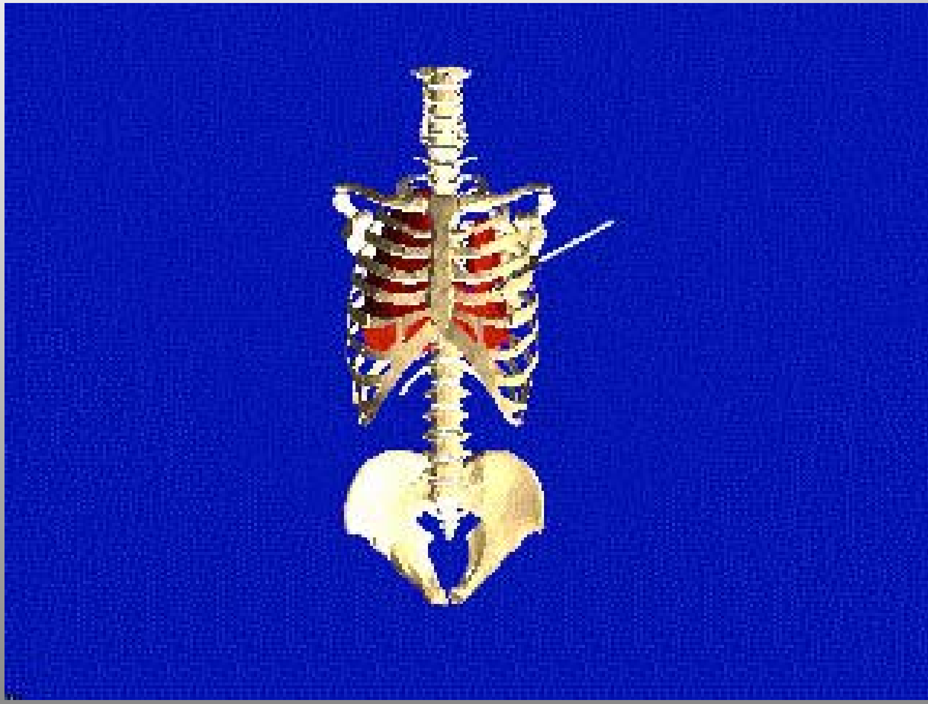


Higher coeff. : number of modules

Results of Single Objective Optimisation

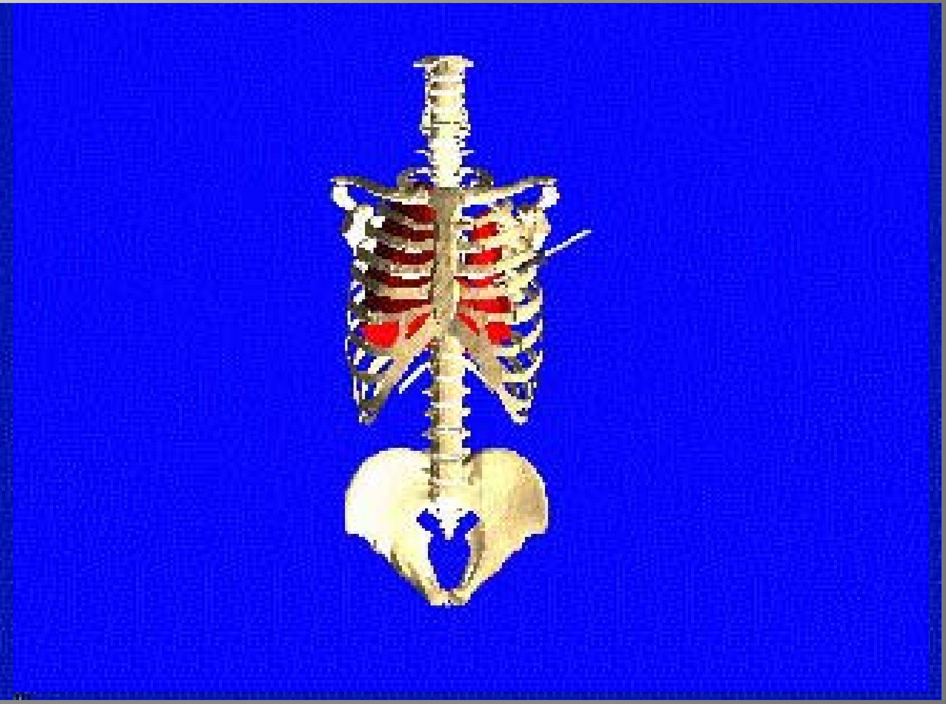
Score = a.Trajectory + b.Manipulability + c.Number of modules

Higher coeff. : manipulability



Base + 25 modules
Module length =minimum

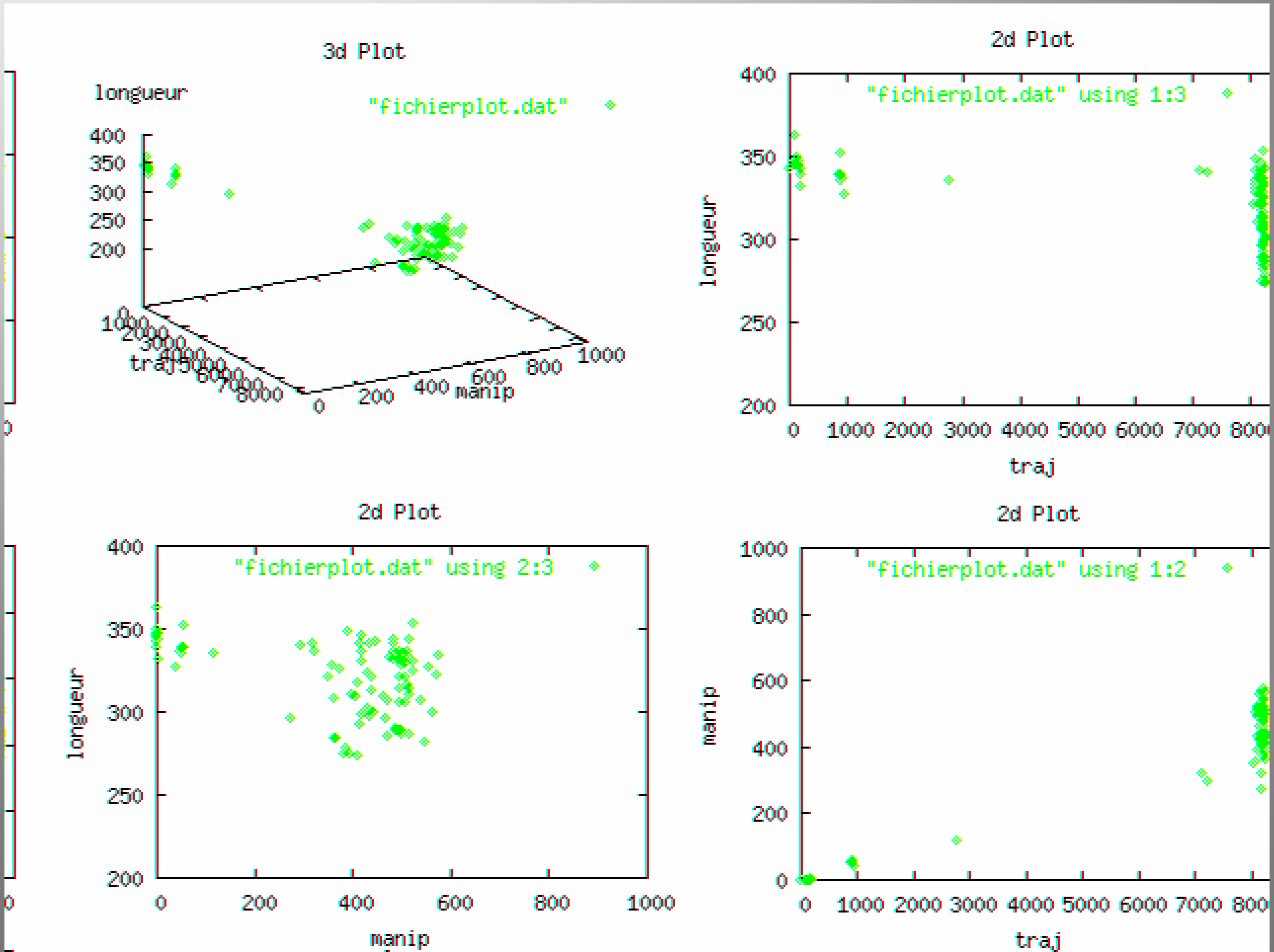
Higher coeff. : number of modules



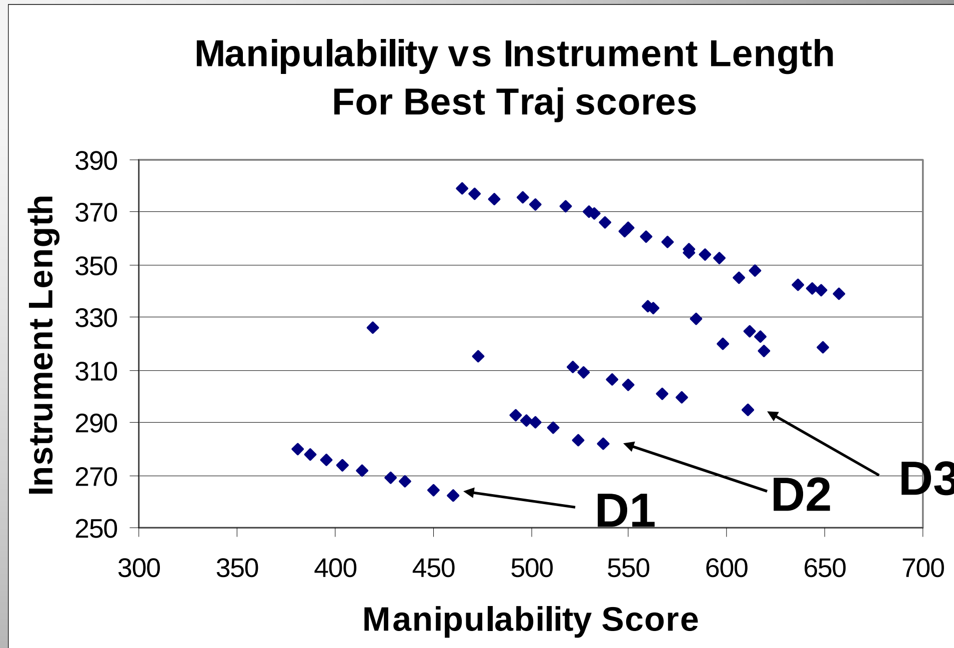
Base + 4 modules
Module length =minimum

Results of Multiple Objective Optimisation

Score1: Trajectory; Score2: Manipulability; Score3: Instrument Length



Instrument selection



	Trajectory	Manip	Length	A	L	A	L	A	L	A	L	A	L	A	L
D1	8252	460	262	3	15.1	3	16.7	1	15.5	2	15.0				
D2	8252	536	281	3	15.3	3	18.1	1	15.2	2	18.2	2	15.0		
D3	8249	611	295	2	16.3	3	16.2	3	16.0	3	15.4	1	15.6	2	15.0

Optimal instrument selection

D1

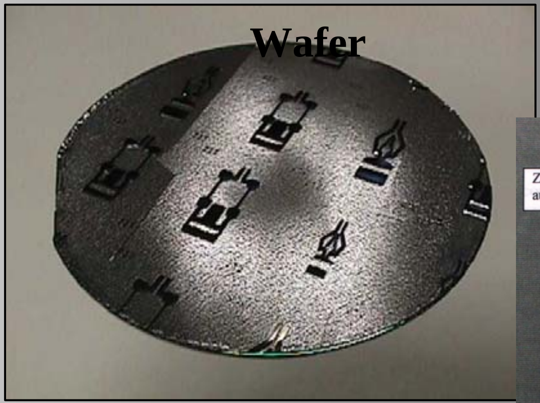
D3

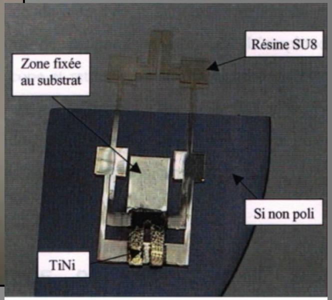
D2

Compliant micromechanisms

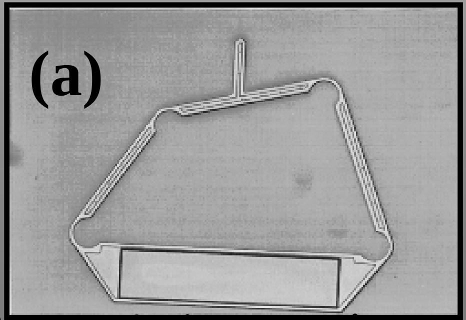
- How to design micromechanical structures which approximate mechanisms ??

(illustration : micro-gripper)

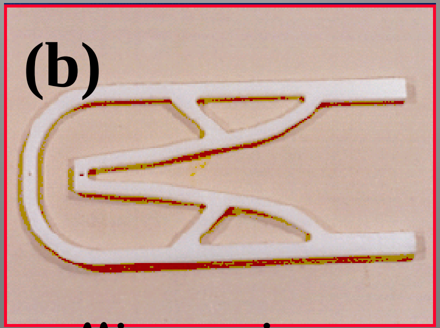




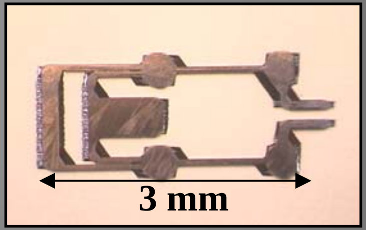
- Lumped (a) or distributed (b) compliance !!



Micro 4 bar mechanism



Micro-gripper



Compliant micromechanisms

- **Main advantages**:

- The reduction in the total number of parts and joints offered by compliant mechanisms is a significant advantage in the fabrication of micro mechanisms.

- Compliant micro mechanisms may be fabricated using technology and materials similar to those used in the fabrication of integrated circuits.

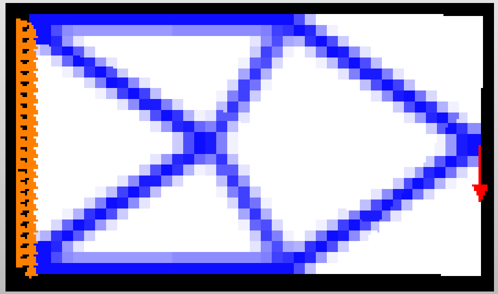
- No friction – no backlash

- Well adapted to distributed actuation

- …

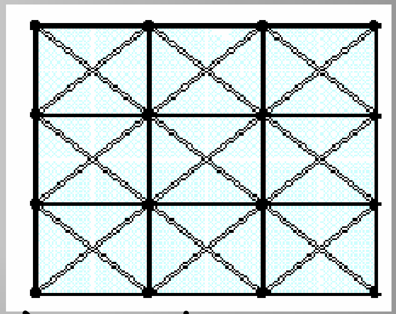
Structural design methods

Homogenisation method

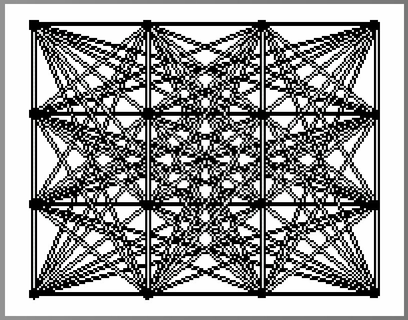


The optimization method solves the problem of distributing a limited amount of material in a design space.

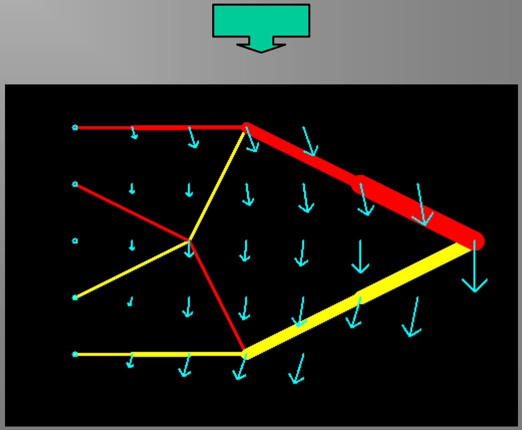
Flexible beam network



(a) ground structure



(b) full ground structure

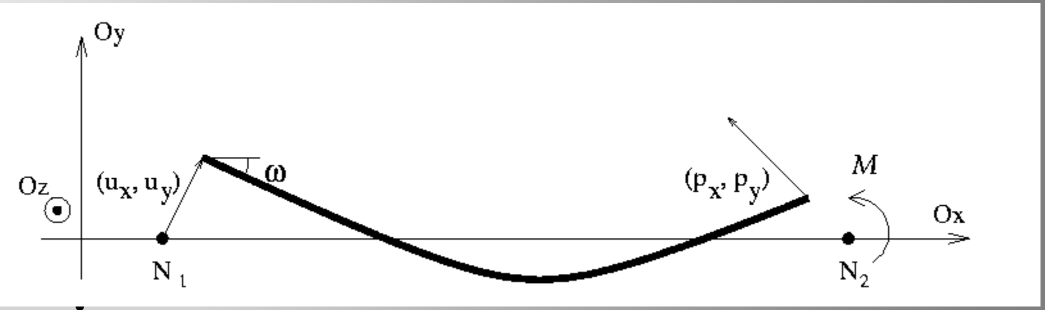


Result from Ipoutre

Compliant micromechanisms

Beam model

- **Beam model :**



- **Traction/compression**

$$\frac{ES}{L}\begin{bmatrix}1 & -1\\ -1 & 1\end{bmatrix}\begin{bmatrix}Ux(1)\\ Ux(2)\end{bmatrix}=\begin{bmatrix}Px(1)\\ Px(2)\end{bmatrix}$$

- **Bending**

$$\frac{2EI}{L^3}\begin{bmatrix}6 & 3 & -6 & 3\\ 3 & 2 & -3 & 1\\ -6 & -3 & 6 & -3\\ 3 & 1 & -3 & 2\end{bmatrix}\begin{bmatrix}Uy(1)\\ Uz(1)\\ Uy(2)\\ Uz(2)\end{bmatrix}=\begin{bmatrix}Py(1)\\ Pz(1)\\ Py(2)\\ Pz(2)\end{bmatrix}$$

$$Uz = w.L$$

$$Pz = \mathrm{M}/L$$

- **General model for a beam oriented by θ :**

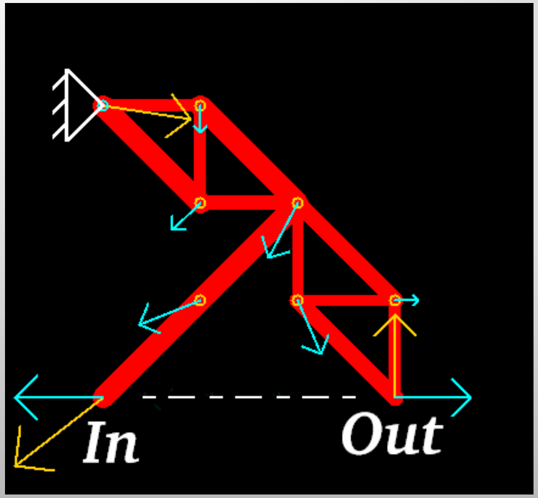
$$R_\theta A_i(m,n)R_{-\theta}\vec{u}(n) = \vec{p}(m)$$

Compliant micromechanisms

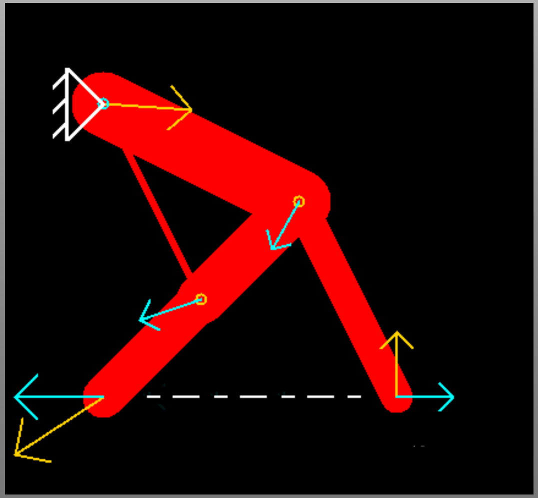
Network model

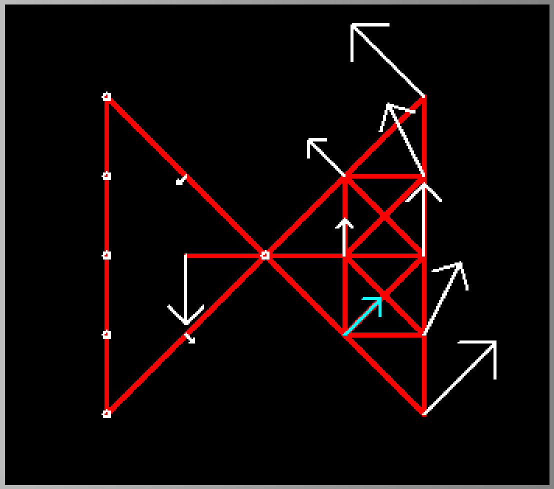
- **Assembling :** $$A = \sum_i A_i$$ $$Au = p$$
- **Multi-load :** K load couples (u^k,p^k)
- **Design variable :** thickness
- **Criteria :** $$Cg = \sum_{n=1}^{N} C(n,n); \qquad C(n,m) = {}^t\vec{u}(n)\,\vec{p}(m)$$
- **Minimal constraints:** minimal threshold - buckling problem
- **Maximal constraints:** volume of material

Compliant micromechanisms
(from Ipoutre)

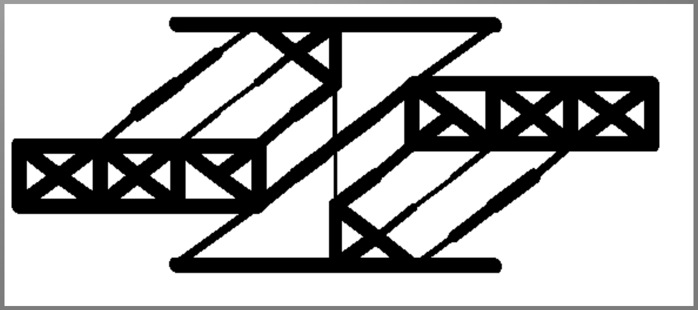


Inverter





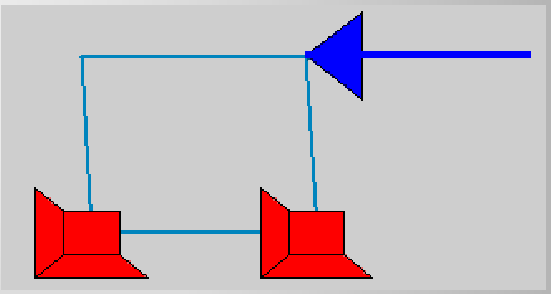
Fixe point

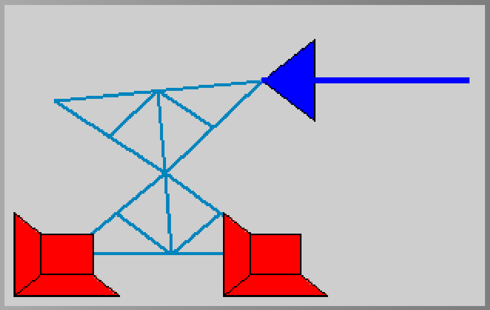


Compliant micromechanisms

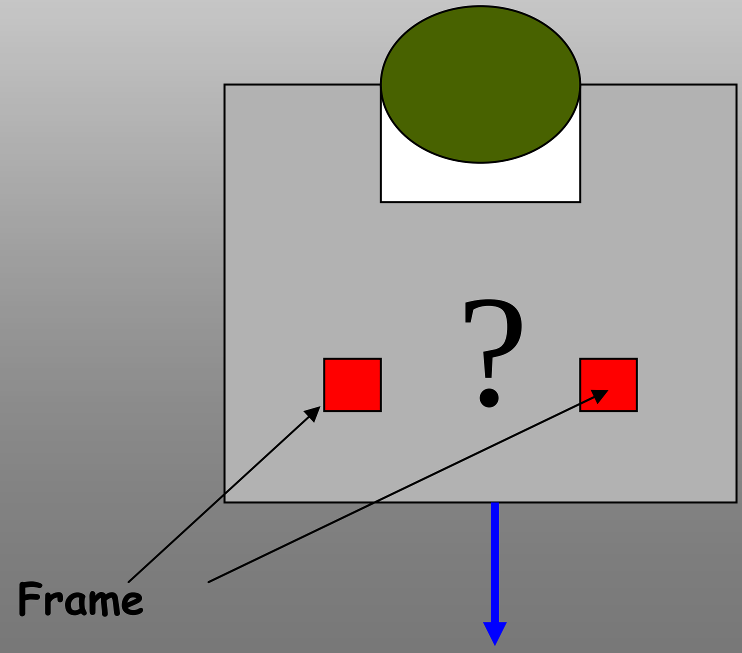
Building block assembly method

- **Building blocks :**





- ***Assembly optimization method :***



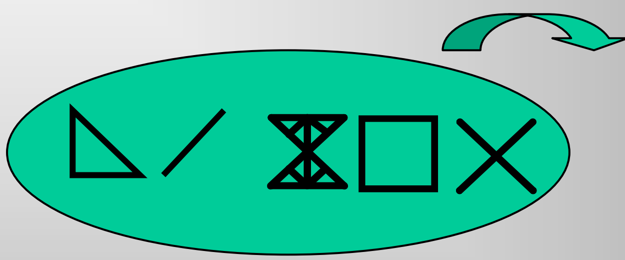
Problem specification :

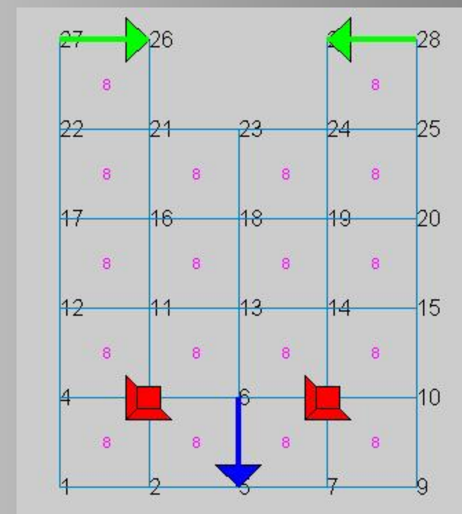
- maximum size : 1.8mm
- object sizes : 0 to 550 microns
- force amplification : 0.2
- displacement amplification : 5
- SDA actuator (max 800 mN)

Compliant micromechanisms

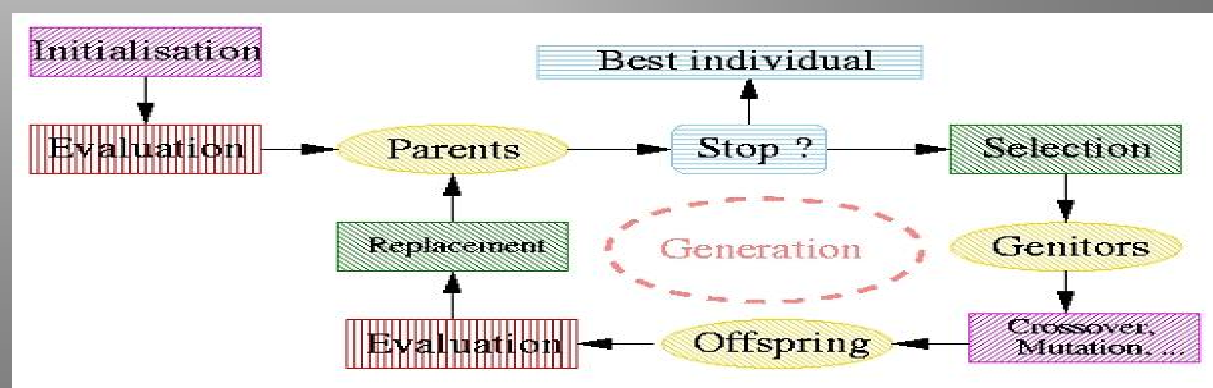
Building block assembly method

- **Design problem and parameters:**





- **Stochastic optimisation :**

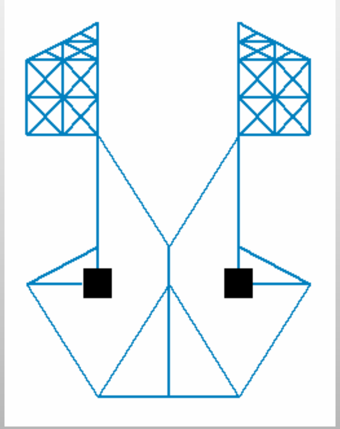


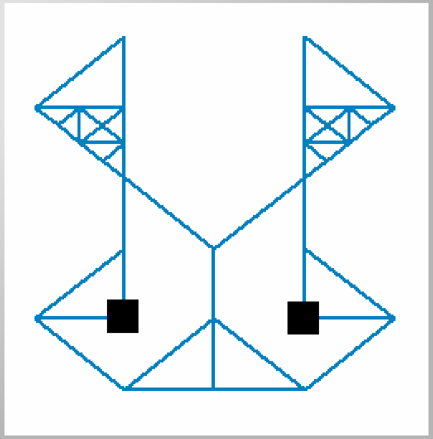
- **Fitness :** Stroke ratio & force ratio

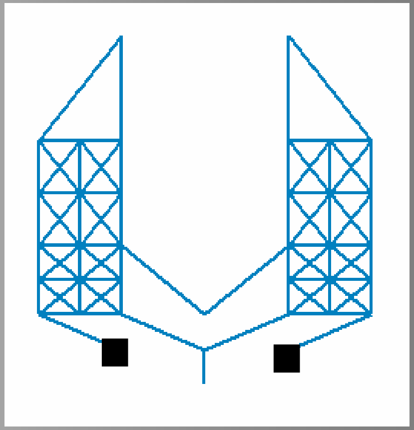
L. R. P.

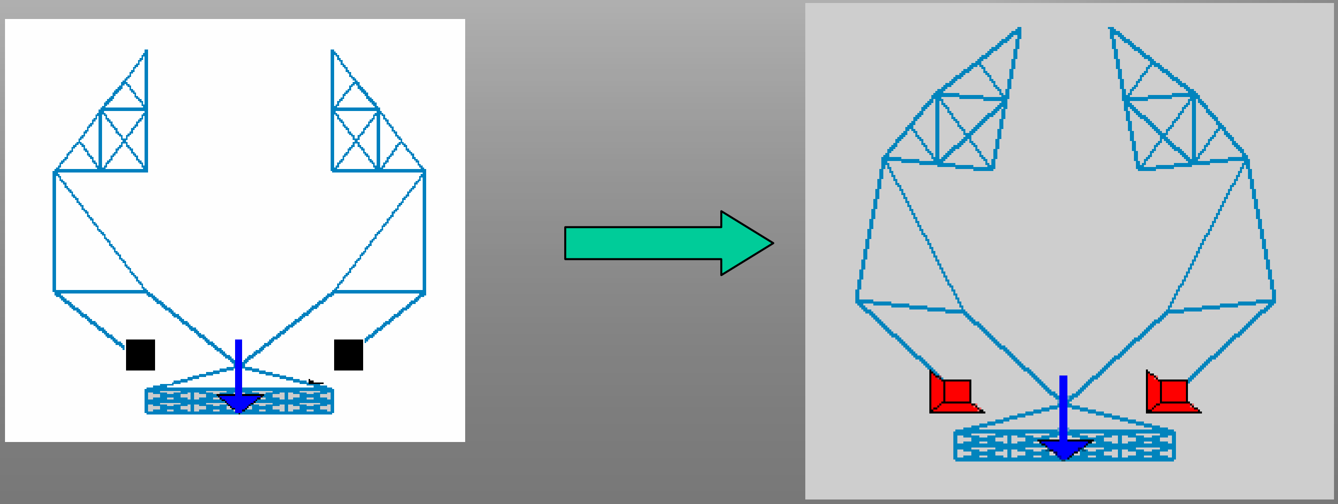
Compliant micromechanisms

- Some optimal solutions :





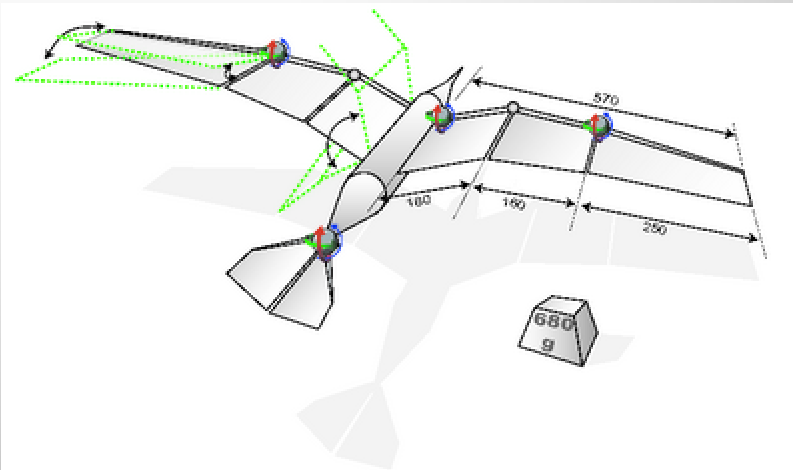


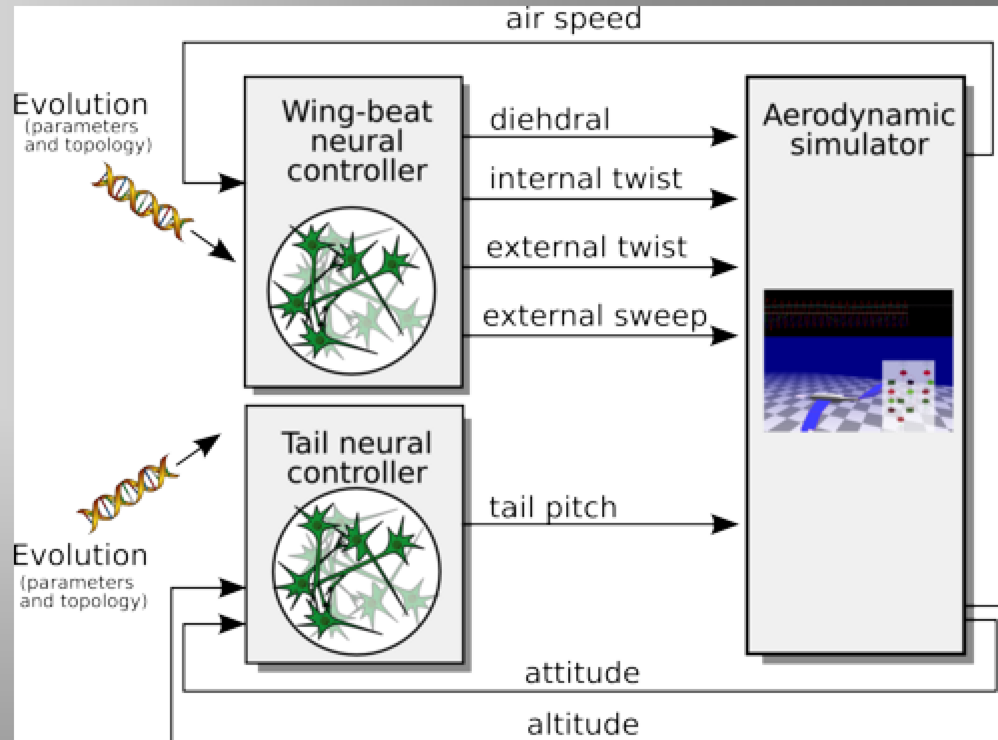


L. R. P.

Rythmic control synthesis

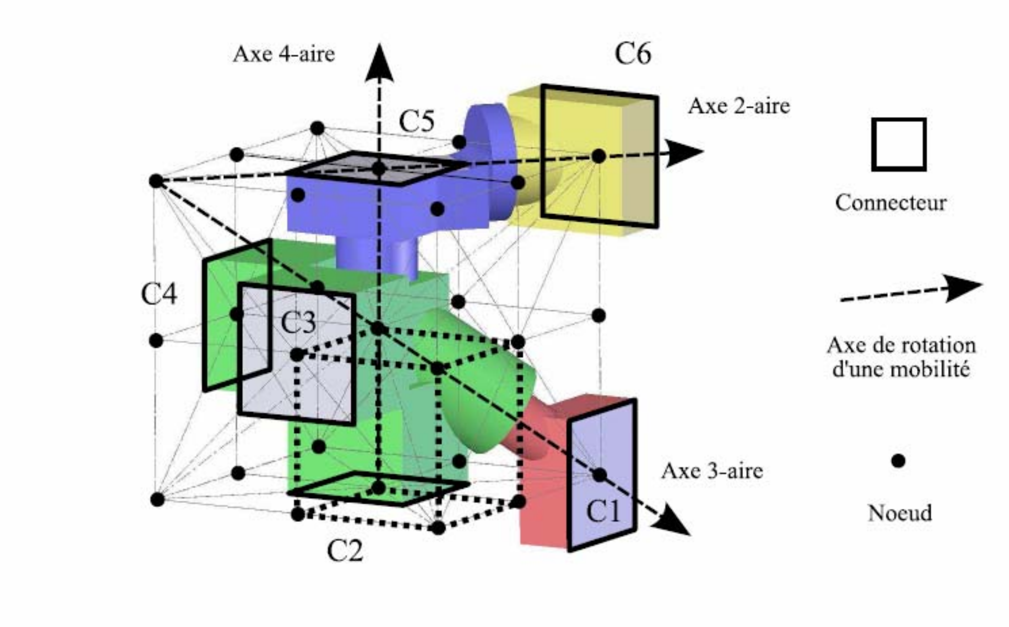
Réseau hybride à oscillateurs non-linéaires et réseaux de neurones

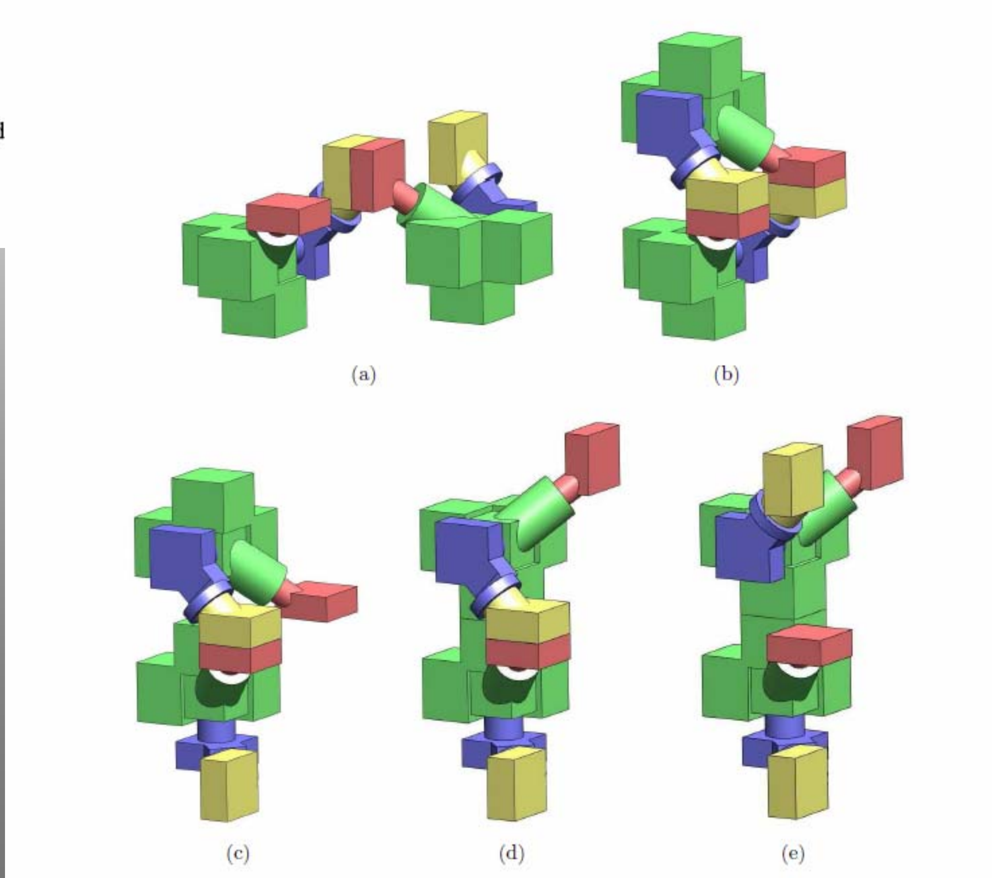




evolving.mp4

Reticular and reconfigurable systems





Tensegrity robots