Modeling and Control of a Hybrid Continuum Active Catheter

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OVERVIEW

1. CONTEXT: aortic aneurysm treatment
2. MALICA: Multi Active Link Catheter
3. MALICA MODELING
4. ORIENTATION CONTROL OF MALICA
5. CONCLUSION

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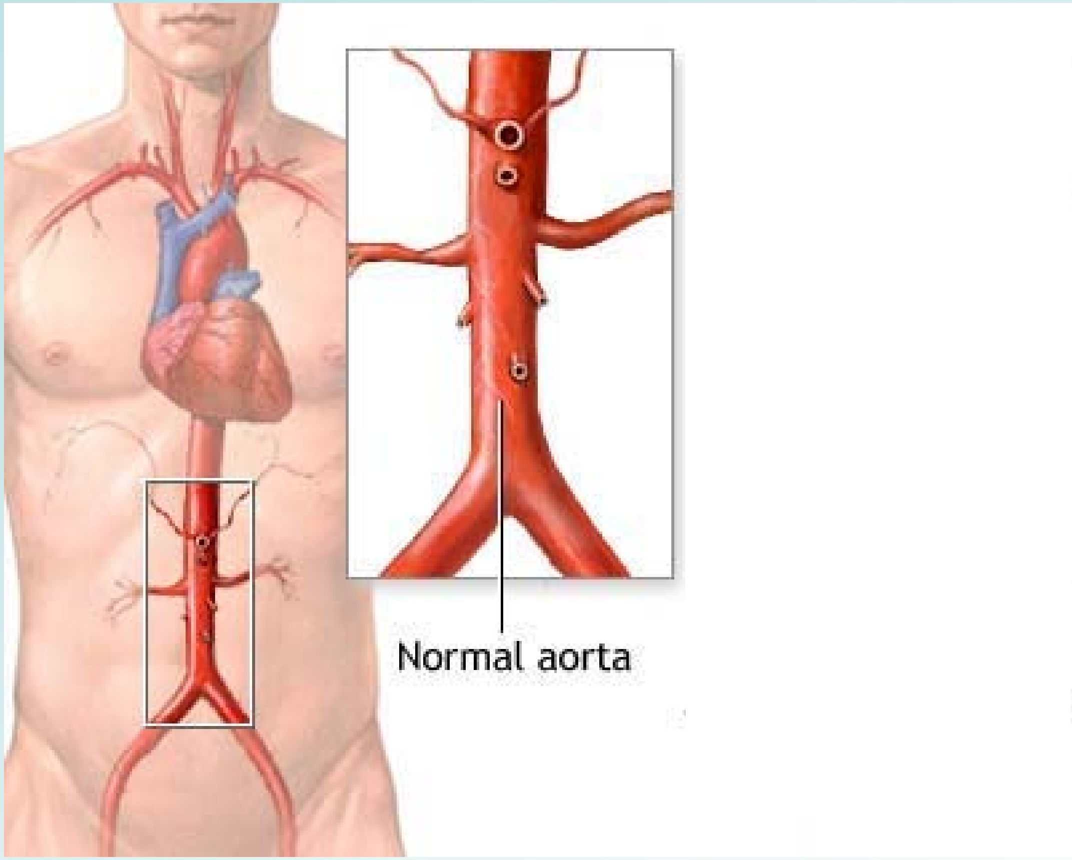
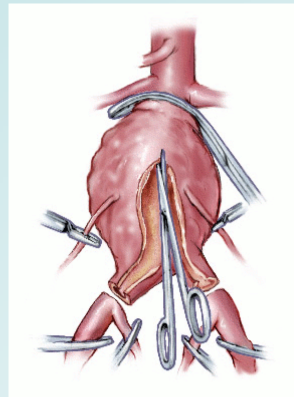
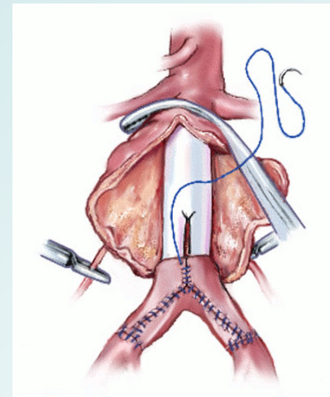
AORTA AND ANEURYSM



- aorta : the biggest artery of the human body
- aneurysm means a marked dilatation of the aorta
  - high mortality rate : 80% to 90%
  - the 13th leading cause of death in the United States

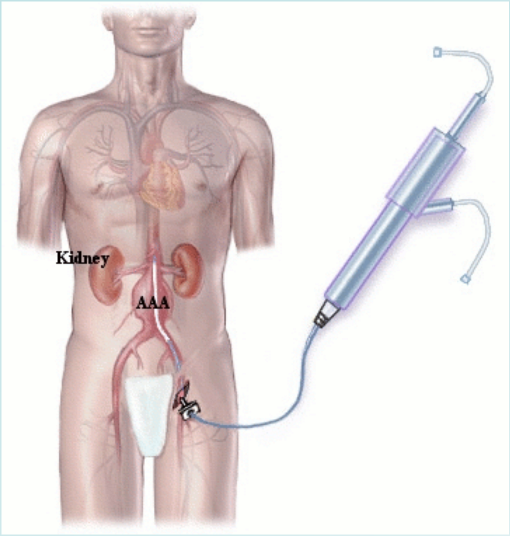
OPEN SURGERY

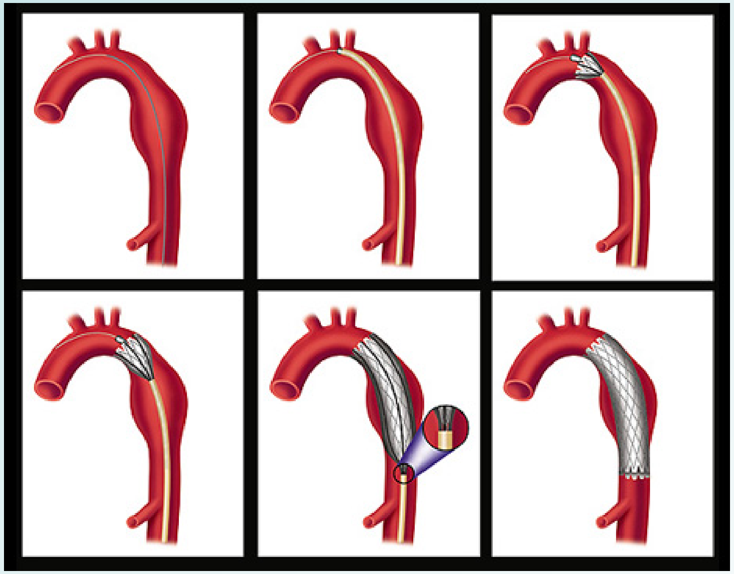




- drawbacks
  - severe procedure
  - long period of hospitalization and convalescence
  - cost

ENDOVASCULAR STENTING



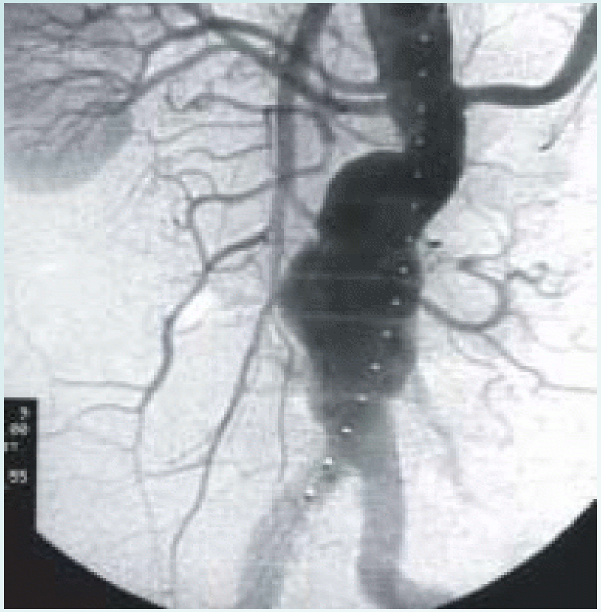


- advantages
  - less trauma
  - shorter hospitalization
  - less expensive
  - cosmetic benefits

DRAWBACKS OF THE MIS PROCEDURE

- **pre-operative stage**
  - selection of the patients
  - dimensioning of the stentgraft
- **per- and post-operative stage**
  - poor tactil and visual feedback
  - loss of dexterity
  - stentgraft delivering
  - possibility of endoleak

DRAWBACKS OF THE MIS PROCEDURE



French Ministry of Research project called **MATEO** (2000-2002) : Arteries Modeling and Computer Aided Endovascular Treatment

- design of a new minimally invasive robotic surgery system

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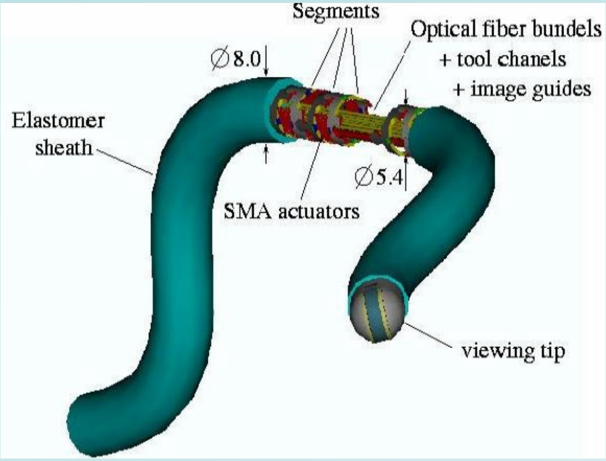
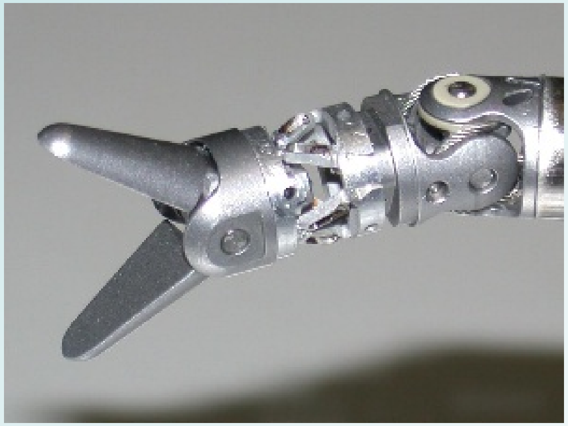
ACTIVE MIS INSTRUMENT EXAMPLES



LRP (Paris 6) – SMA modular actuator



DLR – cable driven joints

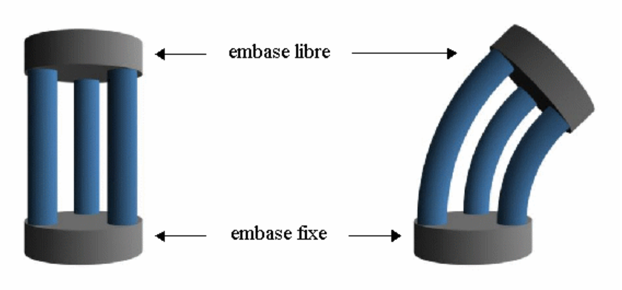
Catholic University of Leuven – cable driven joints

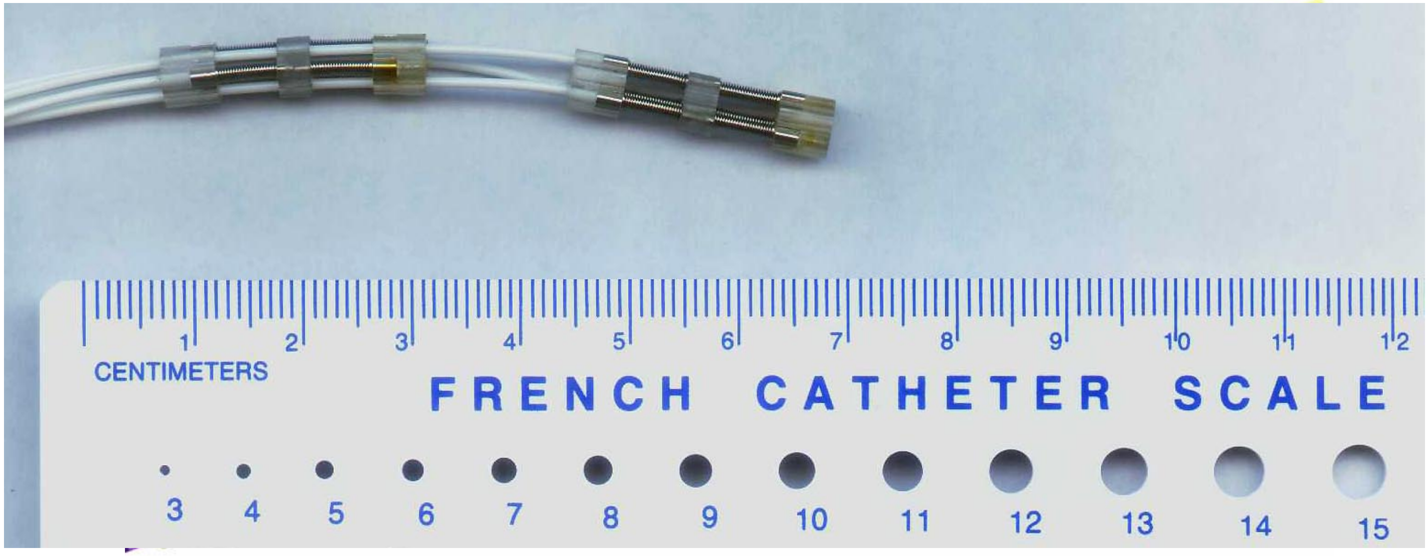
Tohoku University – SMA

MALICA: Multi Active LInk CAtheter

requirements :

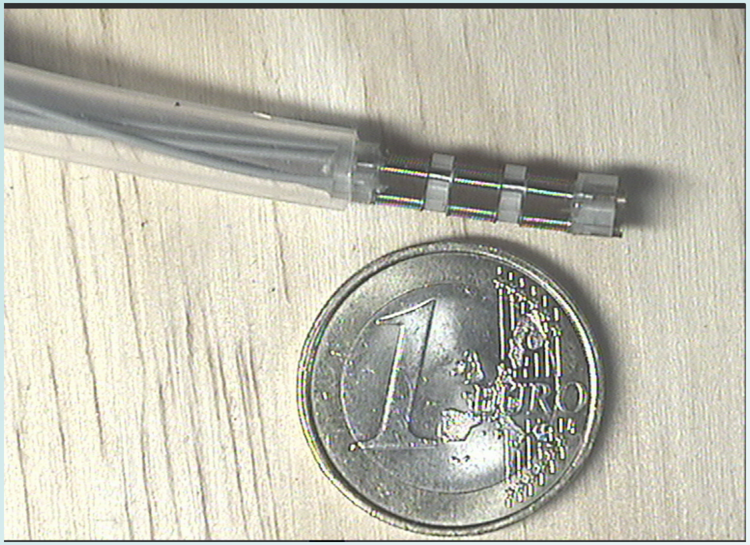
- dimensions
- sterilizable
- dedicated to aneurysm treatment





active catheter

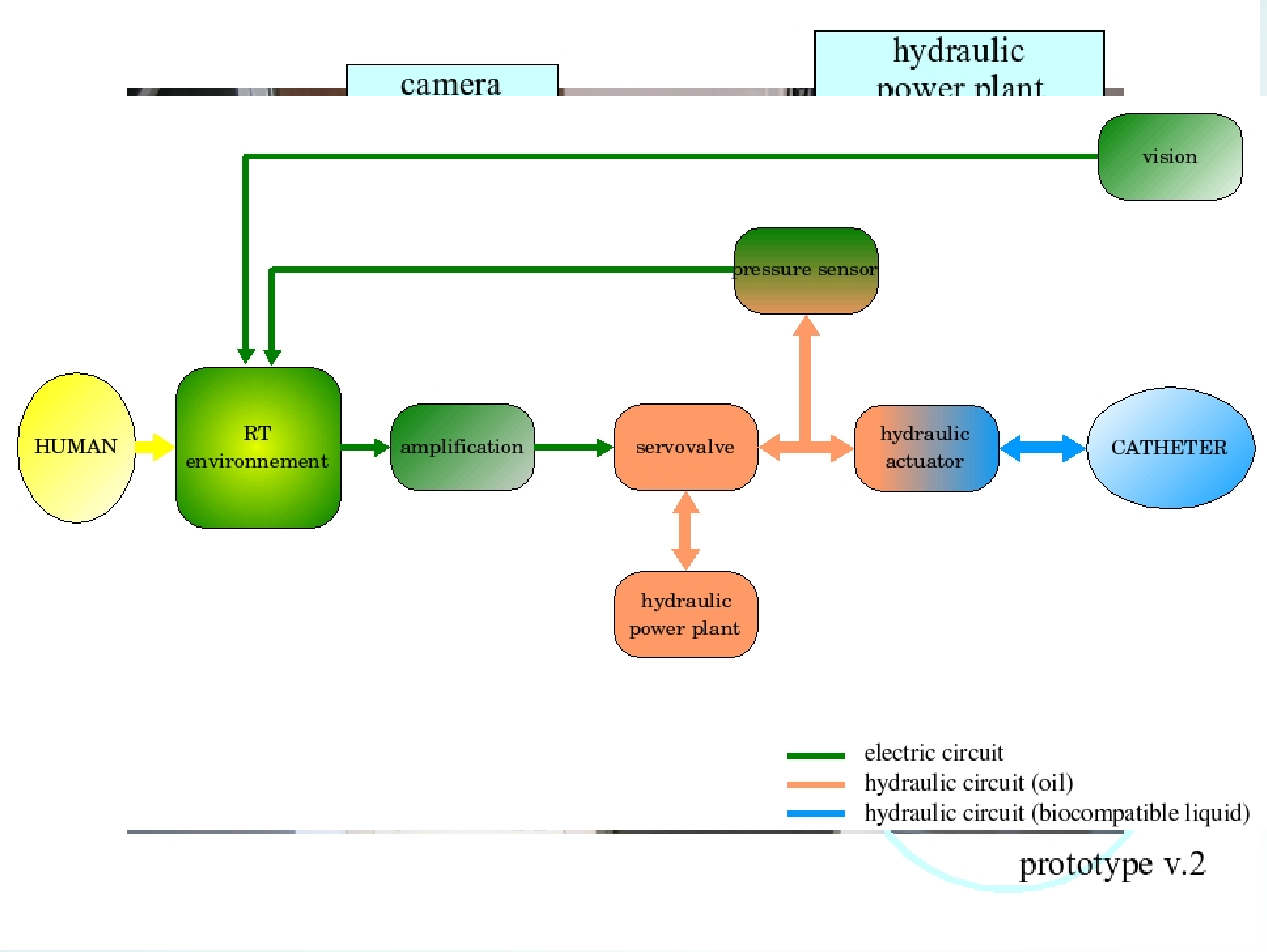
MALICA: Multi Active LInk CAtheter



prototype v.2:

- 4,9 mm outer diameter
- 20 mm length
- a working channel of 2 mm diameter

EXPERIMENTAL SITE



OVERVIEW

1. CONTEXT: aortic aneurysm treatment
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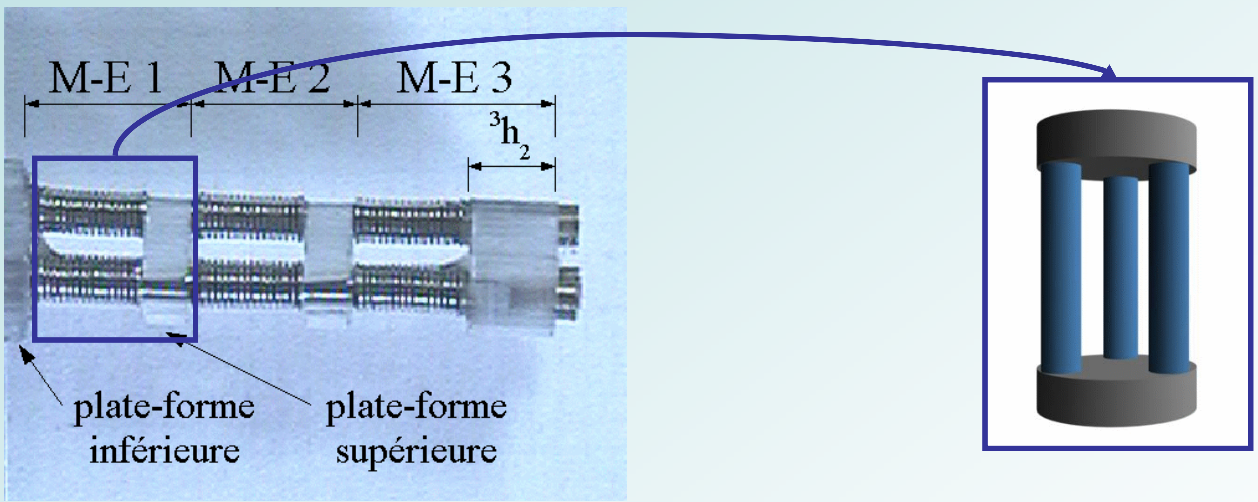
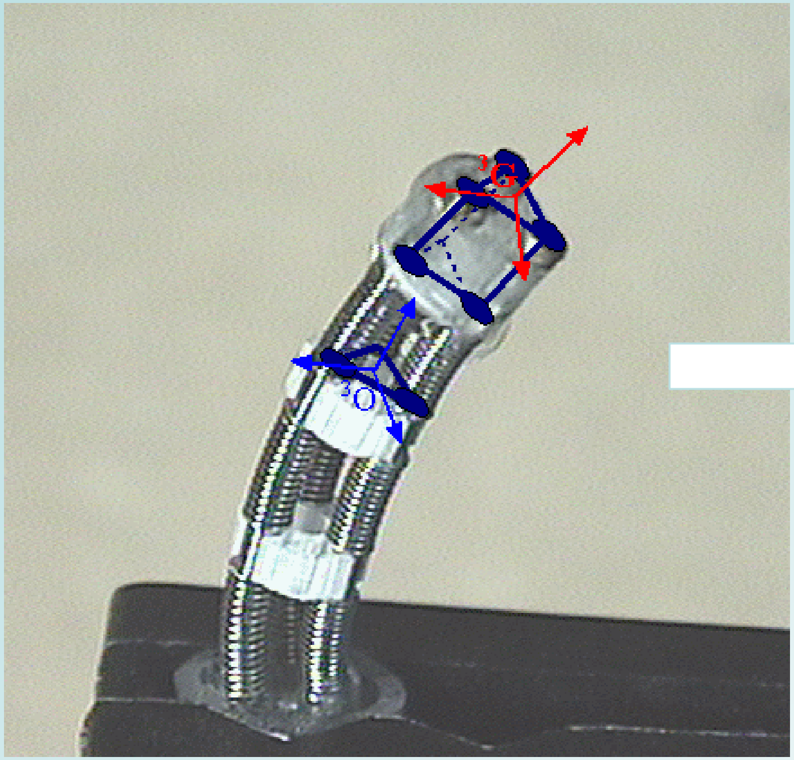
3. MALICA MODELING
   - Nomenclature
   - Direct and Inverse Geometric Model
   - Direct and Inverse Kinematic
4. ORIENTATION CONTROL OF MALICA
5. CONCLUSION

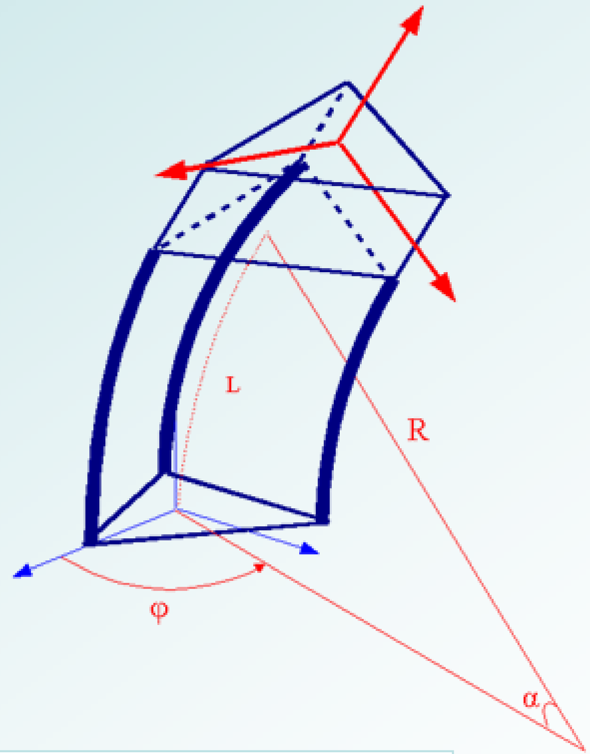
NOMENCLATURE



one micro-robot can be seen as a stack of 3 elementary modules (E-M) with the same behaviour

NOMENCLATURE





3 parameters characterize the E-M bending:

- R : radius of curvature of center line of the E-M
- α : bending angle in the bending plane
- φ : angle of the bending plane

BENDING EXPRESSION OF E-M 1

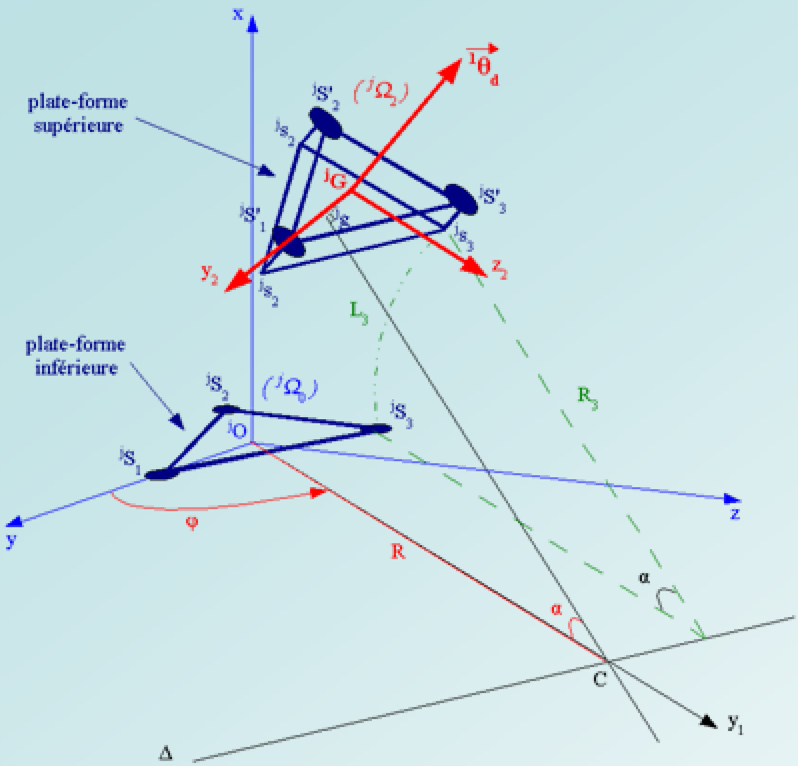


figure 1 : schematic draw of E-M 1

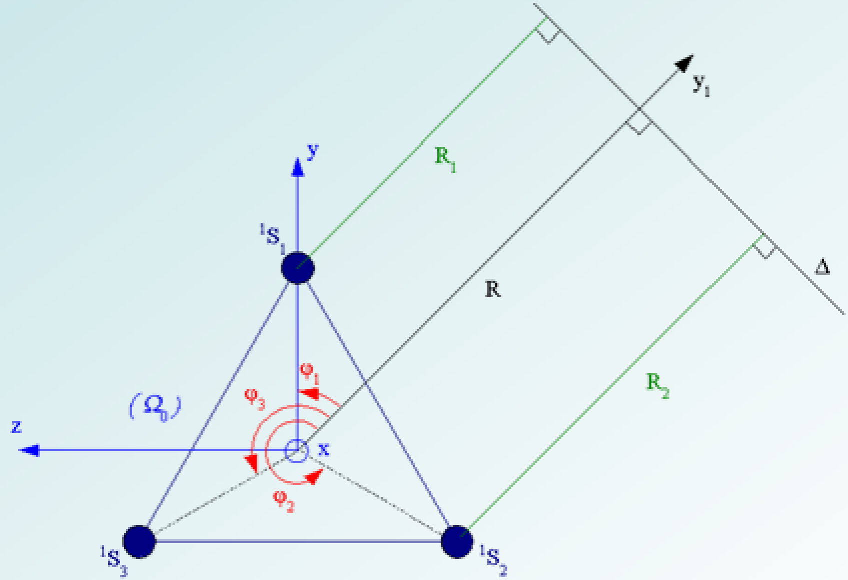


figure 2 : top view of the base coordinate frame

$$\varphi = atan2(\sqrt{3}(L_2 - L_3), L_3 + L_2 - 2L_1)$$

$$R = \frac{h_1 \sum_{i=1}^{3} L_i}{3\sqrt{\xi_l}}$$

$$\alpha = \frac{\sqrt{\xi_l}}{h_1}$$

avec $\xi_l = L_1^2 + L_2^2 + L_3^2 - L_2L_1 - L_3L_1 - L_2L_3$

DIRECT GEOMETRIC MODEL

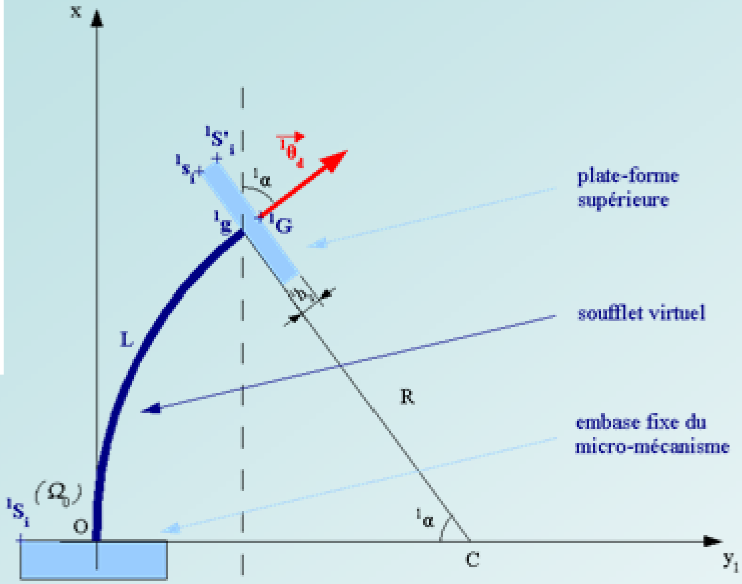


figure : E-M projection in the bending plane

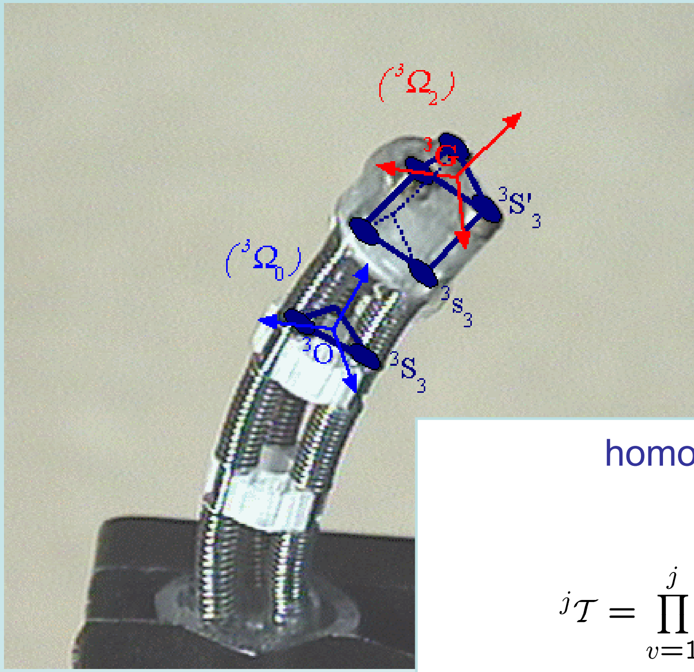
M-E in bending

$$ {}^{j}G = \begin{pmatrix} R \sin\alpha + {}^{j}h_2 \cos\alpha \\ (R(1-\cos\alpha) + {}^{j}h_2 \sin\alpha)\cos\varphi \\ (R(1-\cos\alpha) + {}^{j}h_2 \sin\alpha)\sin\varphi \end{pmatrix} $$

M-E in stretching ($L_1 = L_2 = L_3$)

$$ {}^{j}G = \begin{pmatrix} L_0 + {}^{j}h_2 + \Delta L \\ 0 \\ 0 \end{pmatrix} $$

DIRECT GEOMETRIC MODEL



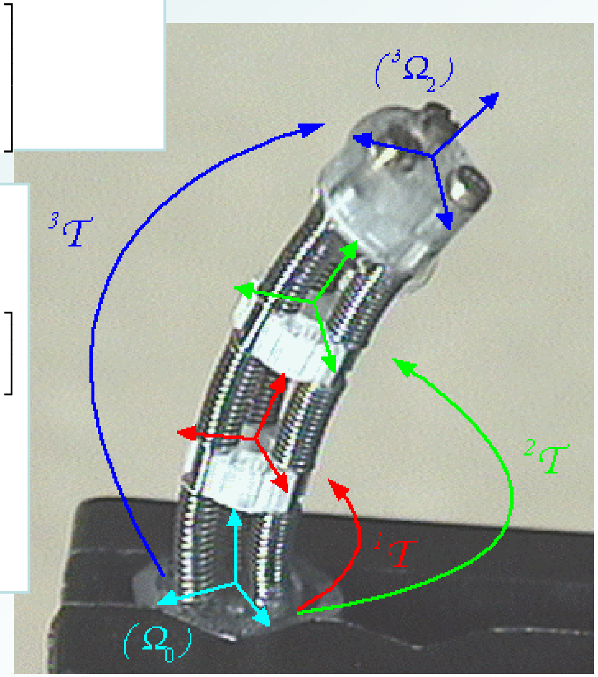
homogeneous matrix of j E-M

$${}^j\mathcal{T} = \prod_{v=1}^{j} \begin{bmatrix} \mathcal{R}_{ot} & \mathcal{P} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & {}^vh_2 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

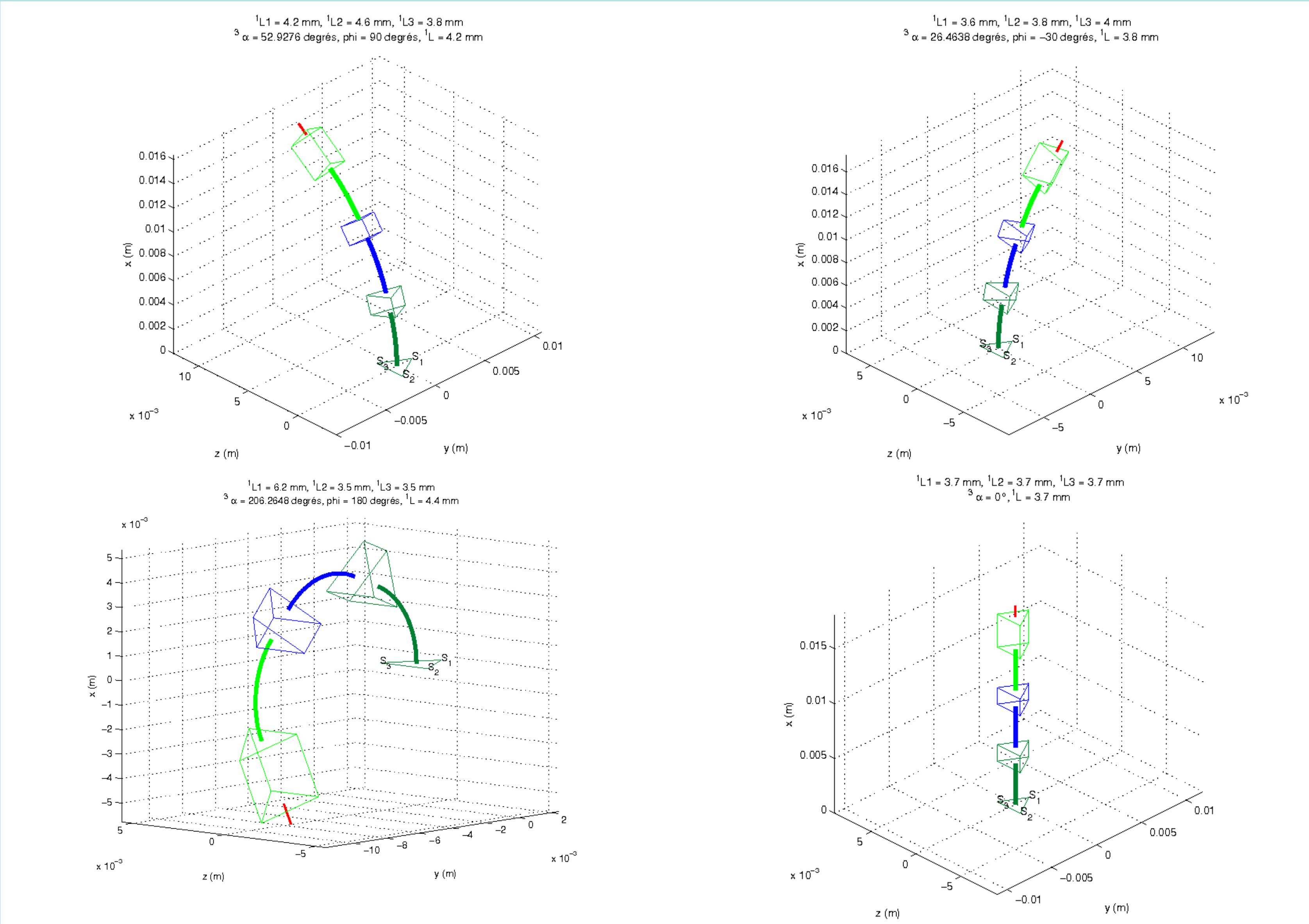
$${}^j\mathcal{P} = {}^j\overrightarrow{O^j g}$$

$$\mathcal{R}_{ot} = \left[{}^j\vec{\theta} \; , \; \frac{{}^1\overrightarrow{g^1 s_1}}{\left\| {}^1\overrightarrow{g^1 s_1} \right\|} \; , \; {}^j\vec{\theta} \wedge \frac{{}^1\overrightarrow{g^1 s_1}}{\left\| {}^1\overrightarrow{g^1 s_1} \right\|} \right]$$

$${}^j\vec{\theta} = \frac{{}^j\overrightarrow{g^j G}}{\left\| {}^j\overrightarrow{g^j G} \right\|}$$



DIRECT GEOMETRIC MODEL



DIRECT GEOMETRIC MODEL

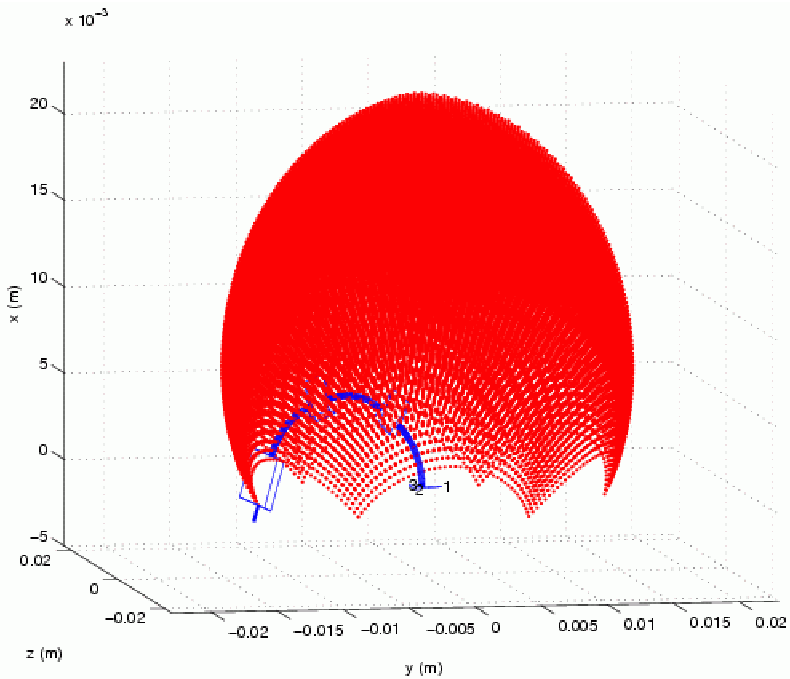


figure 1 : position workspace

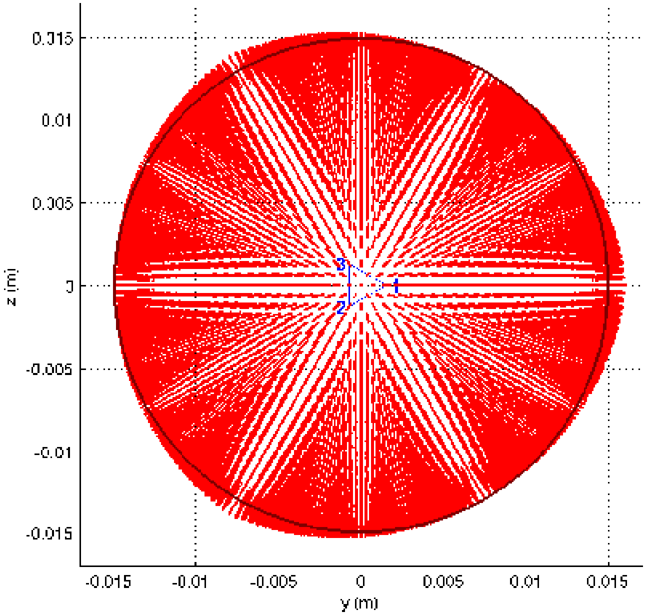
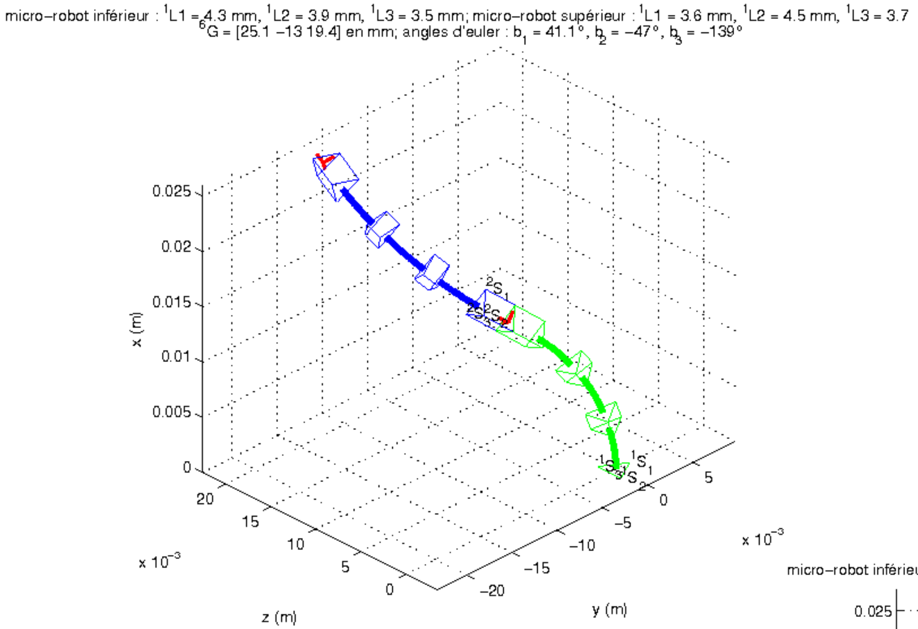
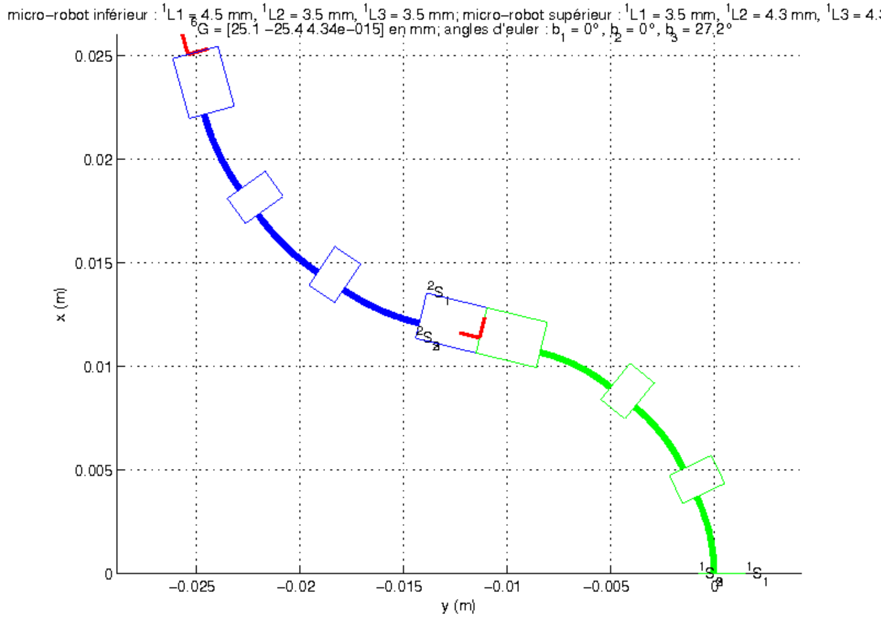


figure 2 : projection on the xy plane

DIRECT GEOMETRIC MODEL





DIRECT KINEMATIC

$$dX = J dq \quad \text{where} \quad J = \frac{\partial X}{\partial q} = \begin{pmatrix} \frac{\partial \alpha}{\partial L_1} & \frac{\partial \alpha}{\partial L_2} & \frac{\partial \alpha}{\partial L_3} \\ \frac{\partial \varphi}{\partial L_1} & \frac{\partial \varphi}{\partial L_2} & \frac{\partial \varphi}{\partial L_3} \\ \frac{\partial R}{\partial L_1} & \frac{\partial R}{\partial L_2} & \frac{\partial R}{\partial L_3} \end{pmatrix}$$

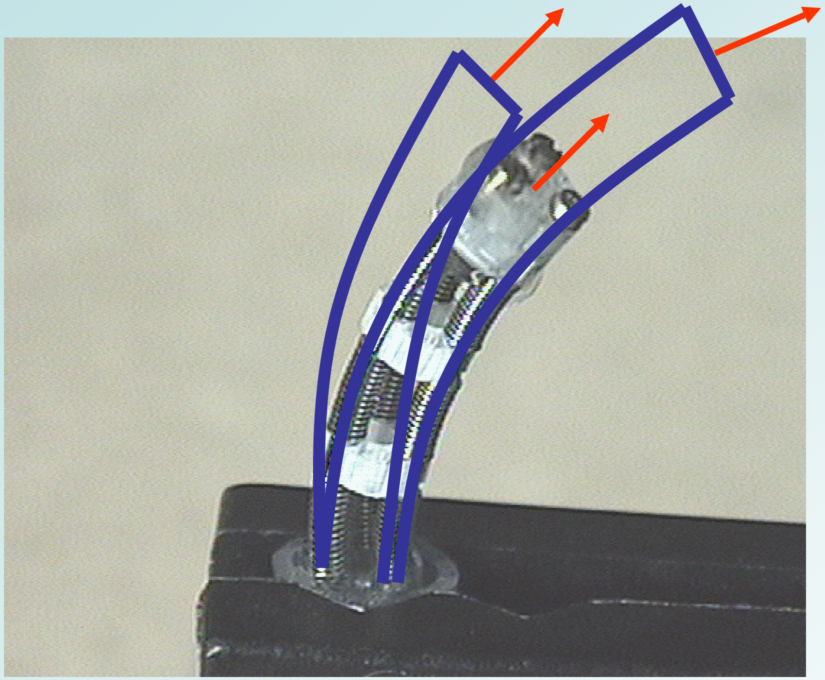
$$\begin{pmatrix} d\alpha \\ d\varphi \\ dR \end{pmatrix} = \begin{pmatrix} \frac{2L_1-L_2-L_3}{2h_1\sqrt{\xi_l}} & \frac{2L_2-L_1-L_3}{2h_1\sqrt{\xi_l}} & \frac{2L_3-L_1-L_2}{2h_1\sqrt{\xi_l}} \\ \frac{\sqrt{3}(L_2-L_3)}{2\xi_l} & \frac{\sqrt{3}(L_3-L_1)}{2\xi_l} & \frac{\sqrt{3}(L_1-L_2)}{2\xi_l} \\ \frac{h_1(L_2^2+L_3^2-L_2L_1-L_3L_1)}{2\xi_l^{\frac{3}{2}}} & \frac{h_1(L_1^2+L_3^2-L_2L_1-L_2L_3)}{2\xi_l^{\frac{3}{2}}} & \frac{h_1(L_1^2+L_2^2-L_3L_1-L_2L_3)}{2\xi_l^{\frac{3}{2}}} \end{pmatrix} \begin{pmatrix} dL_1 \\ dL_2 \\ dL_3 \end{pmatrix}$$

INVERSE KINEMATIC

$$\det J = -\frac{\sqrt{3}}{2\xi_l} \neq 0 \rightarrow dq = J^{-1} d\mathcal{X}$$

$$\begin{pmatrix} dL_1 \\ dL_2 \\ dL_3 \end{pmatrix} = \begin{pmatrix} \frac{h_1 L_1}{\sqrt{\xi_l}} & \frac{L_2 - L_3}{\sqrt{3}} & \frac{\sqrt{\xi_l}}{h_1} \\ \frac{h_1 L_2}{\sqrt{\xi_l}} & \frac{L_3 - L_1}{\sqrt{3}} & \frac{\sqrt{\xi_l}}{h_1} \\ \frac{h_1 L_3}{\sqrt{\xi_l}} & \frac{L_1 - L_2}{\sqrt{3}} & \frac{\sqrt{\xi_l}}{h_1} \end{pmatrix} \begin{pmatrix} d\alpha \\ d\varphi \\ dR \end{pmatrix}$$

INVERSE GEOMETRIC MODEL



- with a constant radius of curvature, variation of the mean length of the bellows change the bending angle of the distal platform
- if we want to keep the same bending angle of the distal platform, we can change either the radius of curvature or the mean length of the bellows

INVERSE GEOMETRIC MODEL

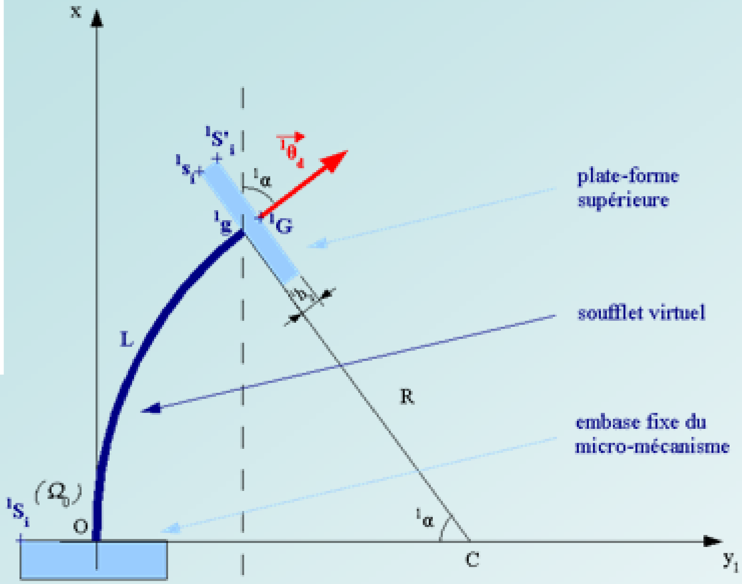


figure : E-M projection in the bending plane

$$^{n}\vec{\theta}_d \;,\; {}^{1}\vec{\theta}_d = \begin{cases} {}^{1}\alpha = \frac{\alpha}{n} \\ {}^{1}\varphi = \varphi \end{cases}$$

$$^{1}\vec{\theta}_d = \begin{cases} a = \cos {}^{1}\alpha \\ b = \cos\varphi \sin {}^{1}\alpha \\ c = \sin\varphi \sin {}^{1}\alpha \end{cases} \Leftrightarrow \begin{cases} {}^{1}\alpha = acos(a) \\ \varphi = atan2(c, b) \end{cases}$$

$$L_i = L - \alpha \frac{2h_1}{3} \cos\varphi_i \qquad L_i \in [L_0, L_0 + \Delta L_{max}]$$

$$\left.\begin{array}{c} L - \alpha \dfrac{2h_1}{3} \cos\varphi_i \geq L_0 \\ L_{max} \geq L \geq L_0 \end{array}\right\} \quad \hat{L} = \underset{L}{\arg\min}\; \psi(L)$$

INVERSE GEOMETRIC MODEL

minimization of the objective function ψ subject to inequalities

$$\hat{L} = \underset{L}{\arg\min}\ \psi(L) \Big| \Big\{ L \geq L_0,\ -L \geq -L_{max},\ L - \alpha\, \frac{2h_1}{3} \cos\varphi_i \geq L_0 \Big\}$$

$$\psi_1 = \frac{1}{2}(R - R_d)^2$$

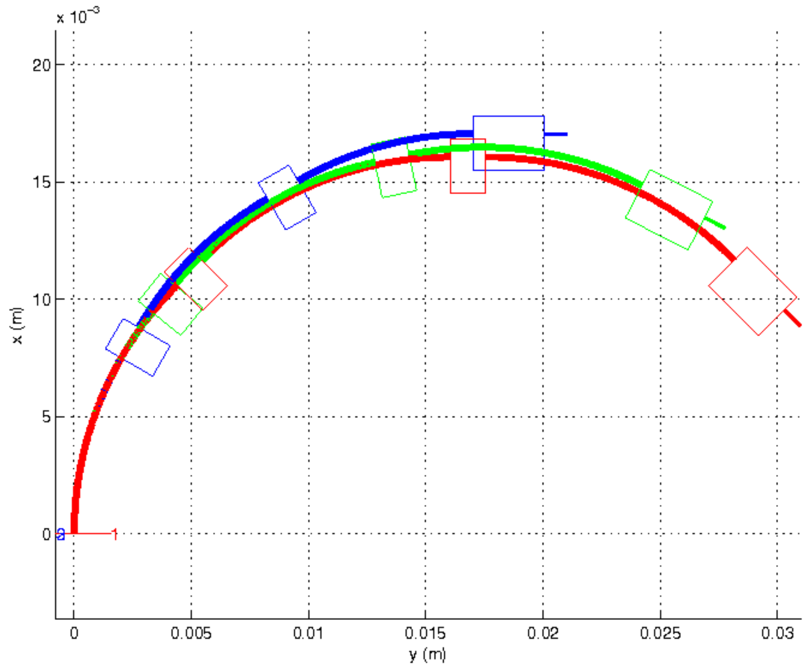


figure : projection in the bending plane

INVERSE GEOMETRIC MODEL

minimization of the objective function ψ subject to inequalities

$$\hat{L} = \arg\min_{L} \ \psi(L) \left| \left\{ L \geq L_0, \ -L \geq -L_{max}, \ L - \alpha \ \frac{2h_1}{3} \cos\varphi_i \geq L_0 \right\} \right.$$

$$\psi_2 = \frac{1}{2}(L - L_d)^2$$

$$\psi_3 = \frac{1}{2}L^2$$

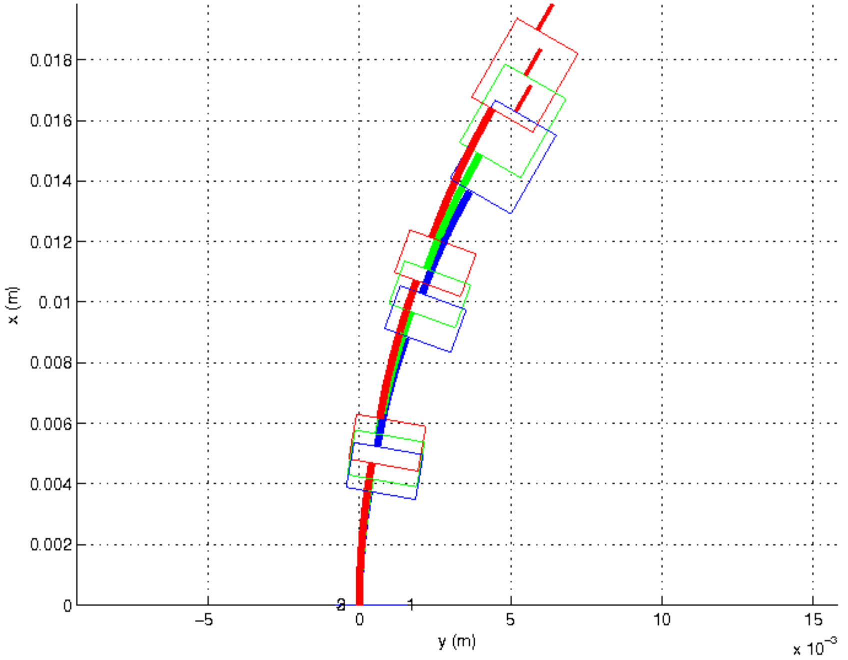
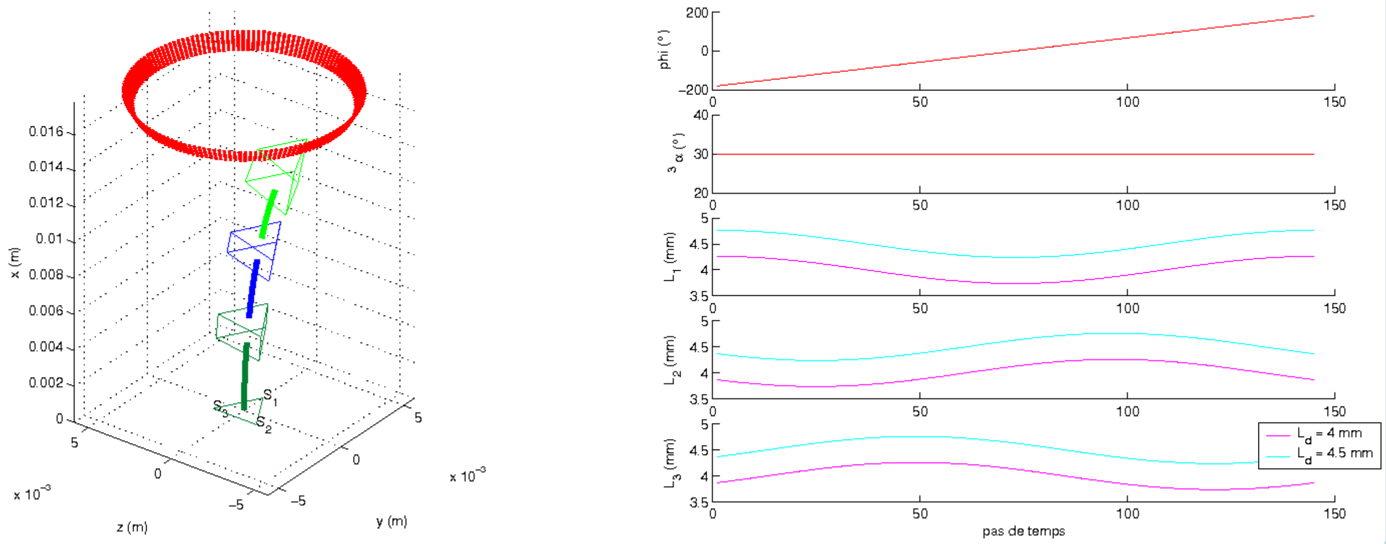


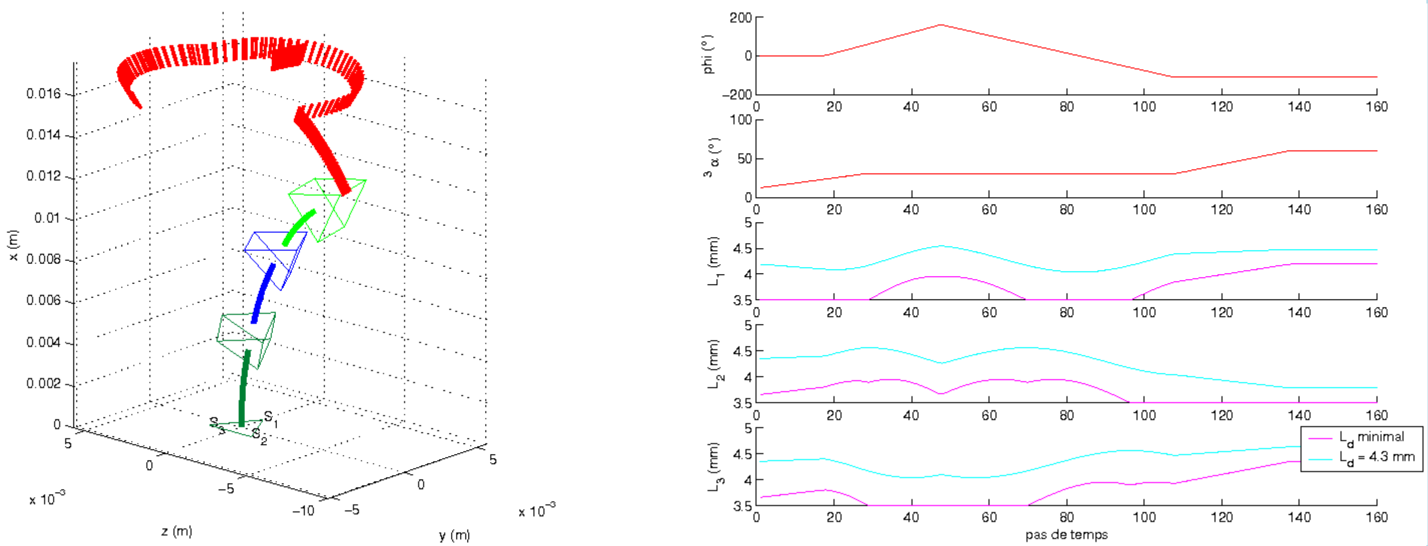
figure : projection in the bending plane

INVERSE GEOMETRIC MODEL

circular trajectory



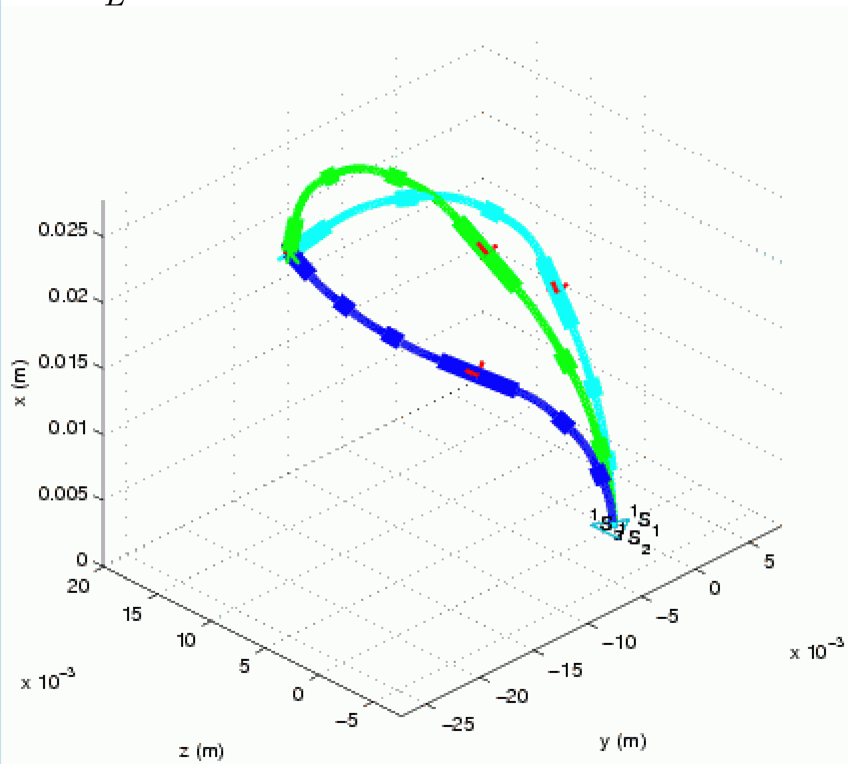
free trajectory

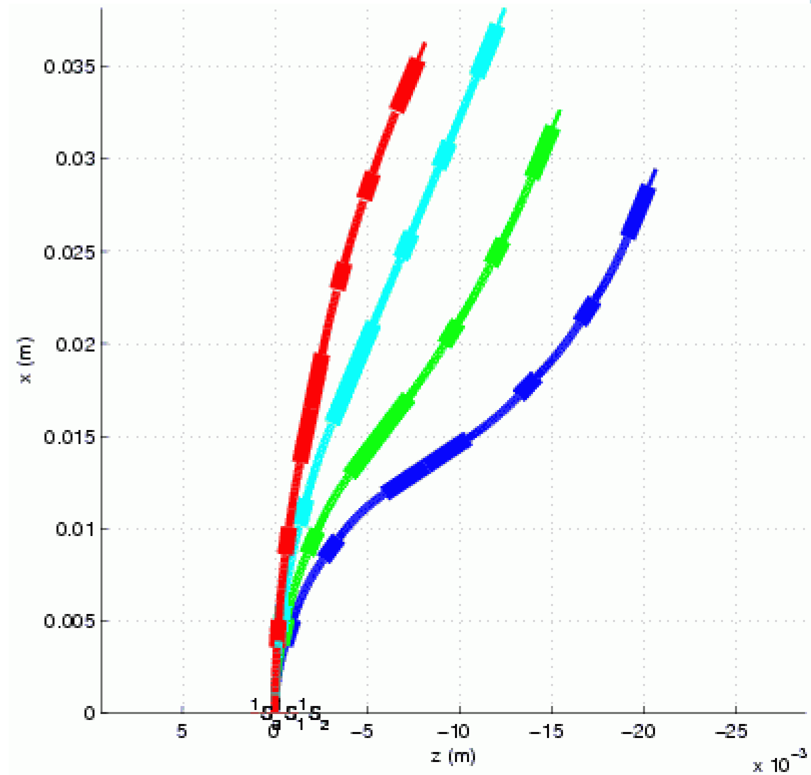


INVERSE GEOMETRIC MODEL

minimization of a the objective function ψ subject to inequalities and equalities

$$\hat{L} = \arg\min_{L} \ \psi(L) \Big| \left\{ L \geq L_0, \ -L \geq -L_{max}, \ {}^6G - Q_d = 0 \right\}$$





$$\hat{L} = \arg\min_{L} \ \psi(L) \Big| \left\{ L \geq L_0, \ -L \geq -L_{max}, \ \vec{\theta}_r - \vec{\theta}_d = 0 \right\}$$

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ORIENTATION CONTROL

$$J^{-1} = \begin{pmatrix} \frac{h_1 L_1}{\sqrt{\xi_l}} & \frac{L_2 - L_3}{\sqrt{3}} & \frac{\sqrt{\xi_l}}{h_1} \\ \frac{h_1 L_2}{\sqrt{\xi_l}} & \frac{L_3 - L_1}{\sqrt{3}} & \frac{\sqrt{\xi_l}}{h_1} \\ \frac{h_1 L_3}{\sqrt{\xi_l}} & \frac{L_1 - L_2}{\sqrt{3}} & \frac{\sqrt{\xi_l}}{h_1} \end{pmatrix} \xrightarrow{AP_i = k\Delta L_i} J_P^{-1} = \begin{pmatrix} \frac{k^2 h_1 P_1}{A^2\sqrt{\xi_P}} & \frac{P_2 - P_3}{\sqrt{3}} & \frac{\sqrt{\xi_P}}{h_1} \\ \frac{k^2 h_1 P_2}{A^2\sqrt{\xi_P}} & \frac{P_3 - P_1}{\sqrt{3}} & \frac{\sqrt{\xi_P}}{h_1} \\ \frac{k^2 h_1 P_3}{A^2\sqrt{\xi_P}} & \frac{P_1 - P_2}{\sqrt{3}} & \frac{\sqrt{\xi_P}}{h_1} \end{pmatrix}$$

criterion : $\psi_1 = \min_L \|R - R_d\|^2$ $\qquad \psi_2 = \min_P \|P - P_d\|^2$

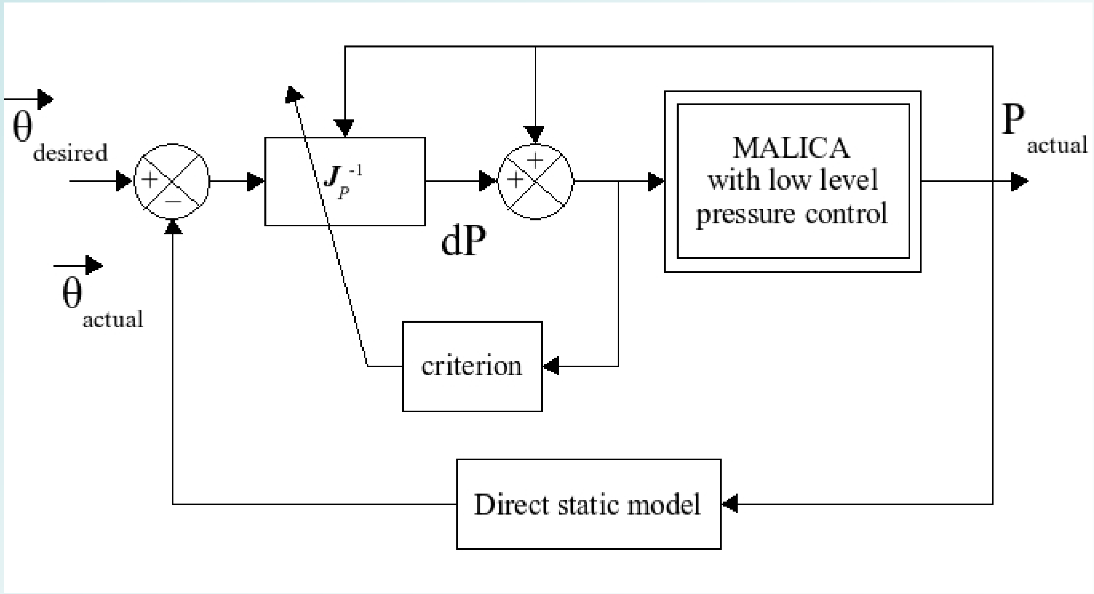

figure : orientation control scheme

ORIENTATION CONTROL

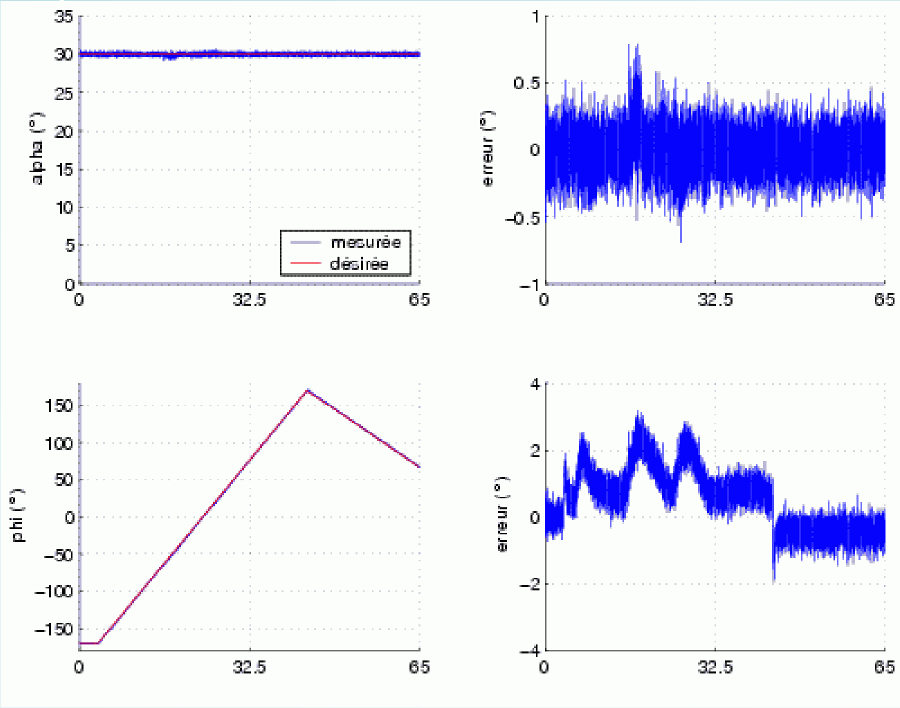

figure 1 : orientation set point

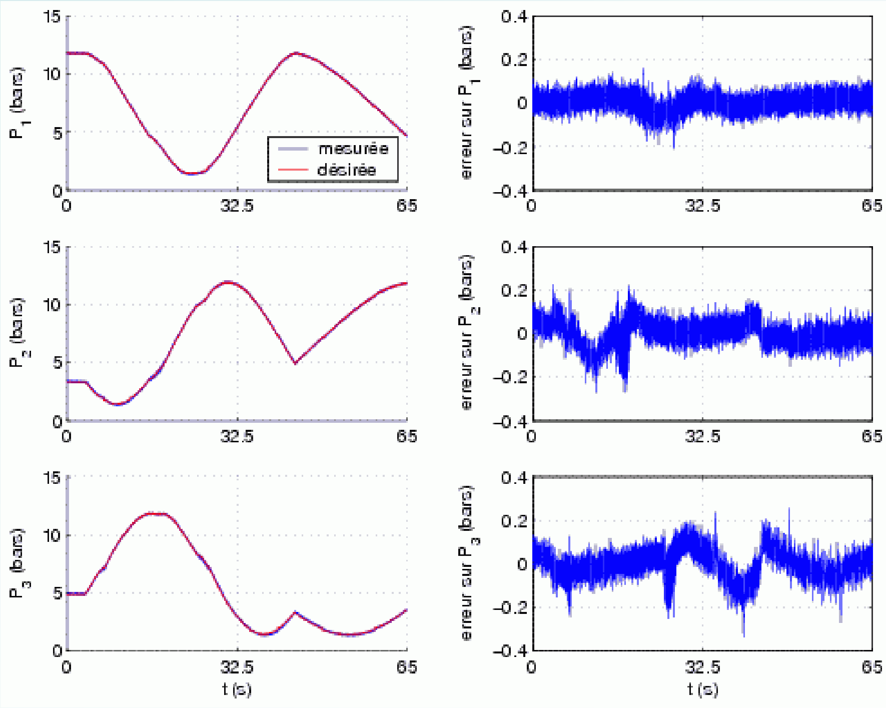

figure 2: bellows pressure

DEMONSTRATION

OVERVIEW

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CONCLUSION

- design of a new generation of active catheters for aortic aneurysm treatment
- new modeling of a hybrid continuum style micro-robot
- orientation control with experimental results