Integration of a force sensor for online estimation of the behaviour of the system and parametrization of the real-time simulation during robotic needle insertion

Virginie MAREC – Master Internship
Supervisors : Hadrien COURTECUISSE
Pedro PERRUSI

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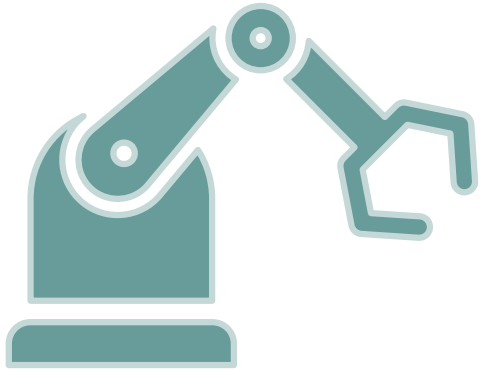
SUMMARY



I – CONTEXT

I - SPERRY (SUPERVISED ROBOTIC SURGERY)

Robotic needle insertion.

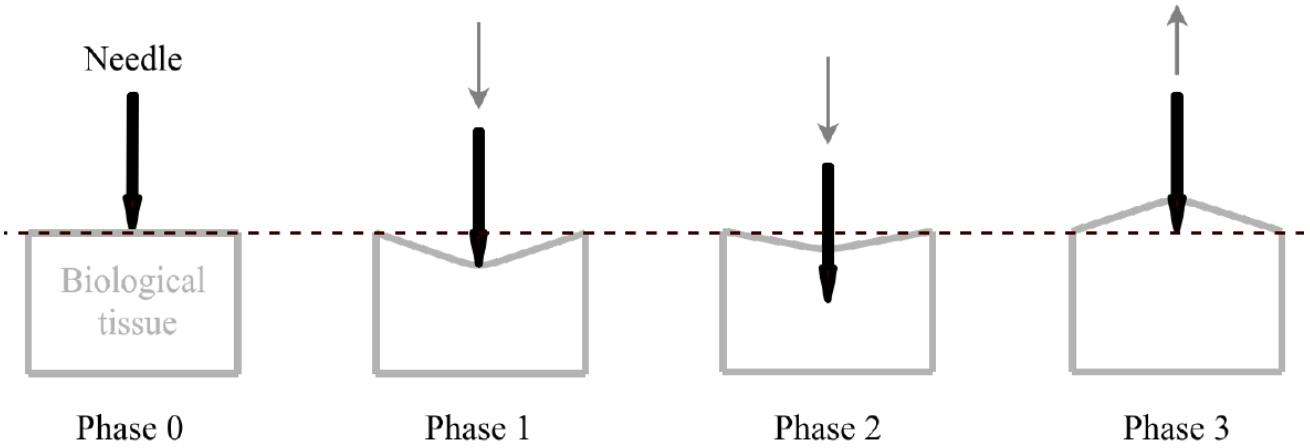
Minimally invasive surgery : Patient comfort, less complications.

Precision (few mm). Manipulated from outside of the patient.

Chirurgical robots : precision + dof.
Limit : hard to predict tissue and needle deformations during insertion.

SPERRY : Prediction of deformations + command of the robot : precise insertion.

I - ROBOTIC NEEDLE INSERTION

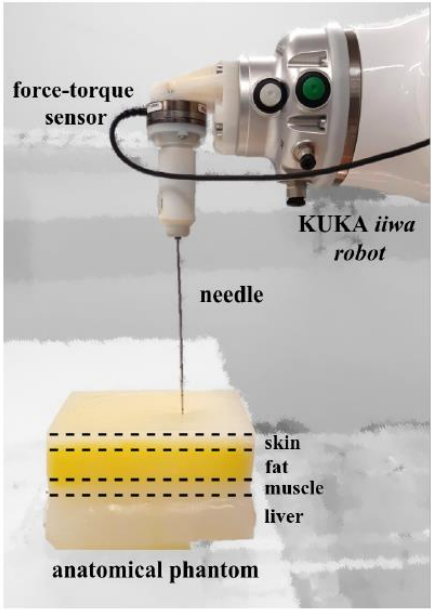


- Force modelling : $f_{needle}(x) = f_{stiffness}(x) + f_{friction}(x) + f_{cutting}(x)$ [1]

- Phase 0 : Needle-Tissue contact.
- Phase 1 : Deformation of the tissue by the needle. Stiffness force due to elastic properties of the tissue.
- Phase 2 : Puncture. Cutting forces + friction forces opposed to this movement.
- Phase 3 : Extraction.

I - MY OBJECTIVES

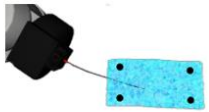
Motivations : test the model already implemented (insertion + friction)
Does it correspond to reality ?



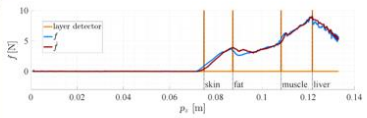
Robotic needle insertion

Forces measurements thanks to a force sensor placed at the base of the needle

Control of the model according to the detected events



Real-time simulation



Event detection algorithm :
- Layer change
- Friction coefficient estimation

II – STATE OF THE ART

II - FORCES APPLIED DURING INSERTION

$$f_{needle}(x) = f_{stiffness}(x) + f_{friction}(x) + f_{cutting}(x) \quad [1]$$

- Stiffness : due to elastic properties of the tissue

$$f_{stiffness}(x) = \begin{cases} 0 & \text{before puncture} \\ f(x) & \text{during puncture} \\ 0 & \text{after puncture} \end{cases} \quad \text{with} \quad f(x) = ax + bx^2 \quad [1]$$

$$f(x) = \frac{x}{ax + b} \quad [2]$$

- Friction : non-linear phenomenon, due to Coulomb friction, tissue adhesion and damping (Dahl's model, Karnopp's model). [1][3]

- Cutting : necessary to cut the tissue at the tip of the needle

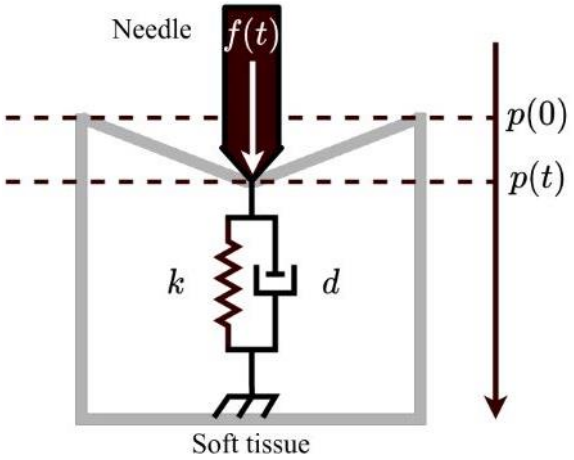
$$f_{cutting}(x) = \begin{cases} 0 & \text{before puncture} \\ c & \text{during puncture} \end{cases}$$

II - TISSU ELASTICITY ESTIMATION

- Compare deformations between real model and simulated model.

  ✗ Tissue characterized by Young Modulus and Poisson coefficient [4]

  ✓ Interaction described by a mass-spring system (Kelvin-Voigt model) [5][6]



- Needle-tissue interaction :

$$f(t) = \begin{cases} k(t)(p(t) - p(0)) + d(t)v(t) & \text{if } p(t) > 0 \\ 0 & \text{if } p(t) \leq 0 \end{cases}$$

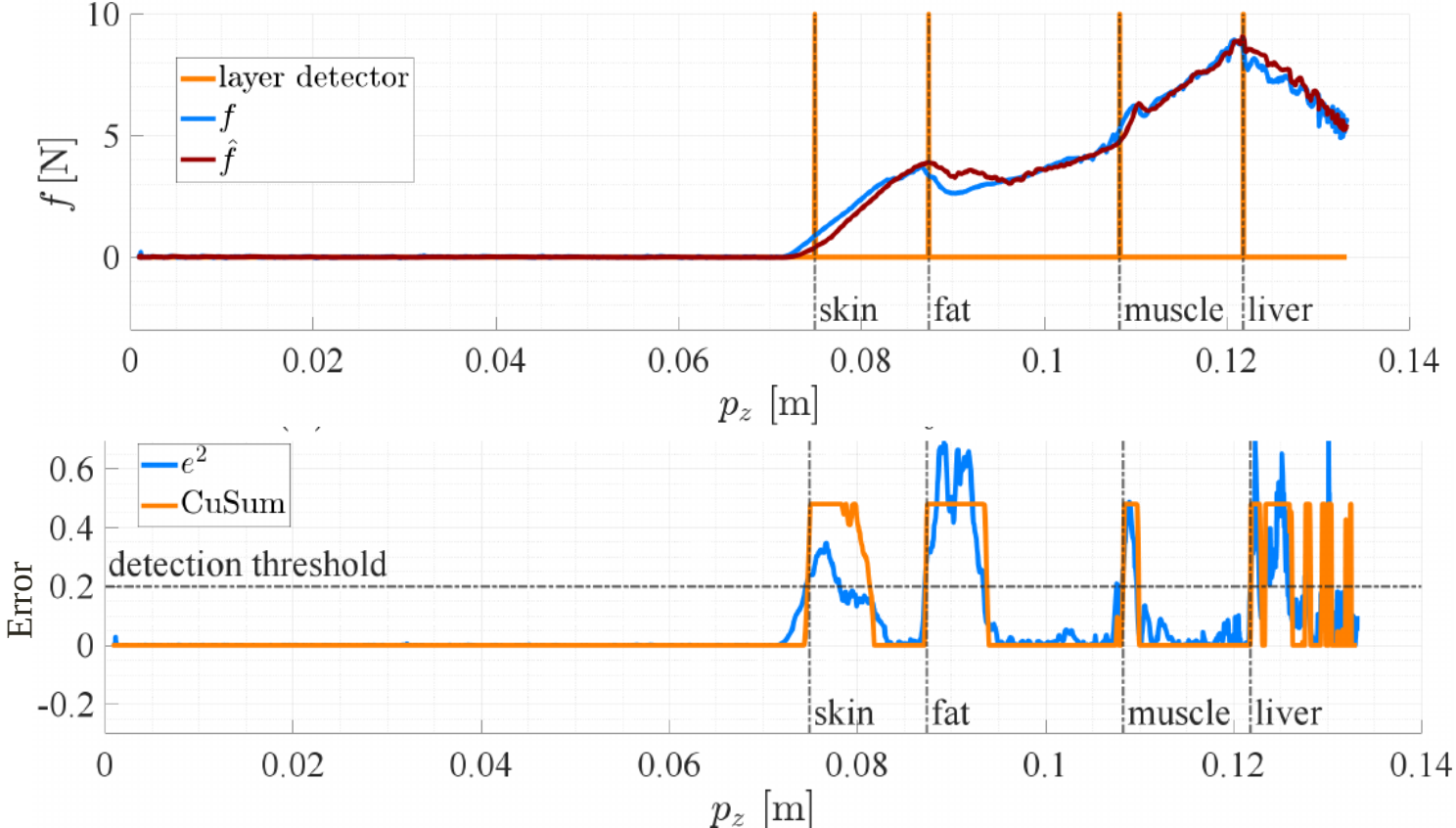
- Discrete formulation :

$$\hat{y}_k = \Phi_k^T \hat{\Theta}_{k-1} \quad \text{with} \quad \Phi_k^T = [p_k - p_0 \quad v_k] \quad \Theta_k = [k_k \quad d_k]^T$$

- Recursive Least Square algorithm :

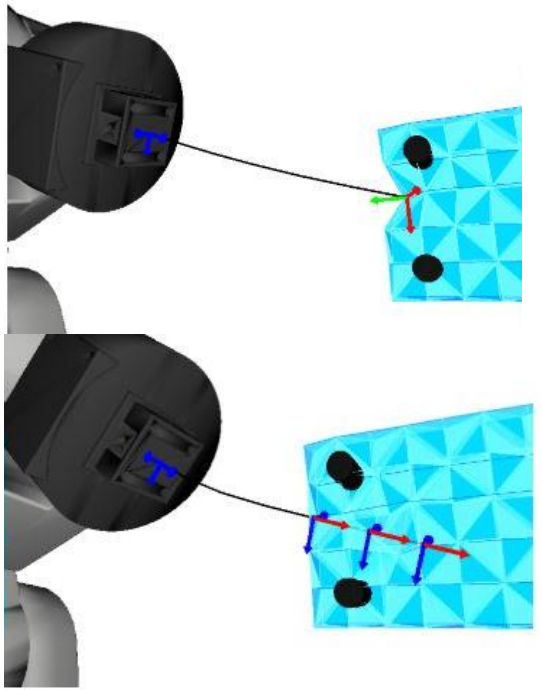
$$\hat{\Theta}_k = \hat{\Theta}_{k-1} + L_k e_k \quad \text{with} \quad \text{Error : } e_k = y_k - \Phi_k^T \hat{\Theta}_{k-1} \quad \text{Gain matrix : } L_k = \frac{P_{k-1}\Phi_k}{\lambda + \Phi_k^T P_{k-1} \Phi_k}$$

II - LAYER CHANGE DETECTION



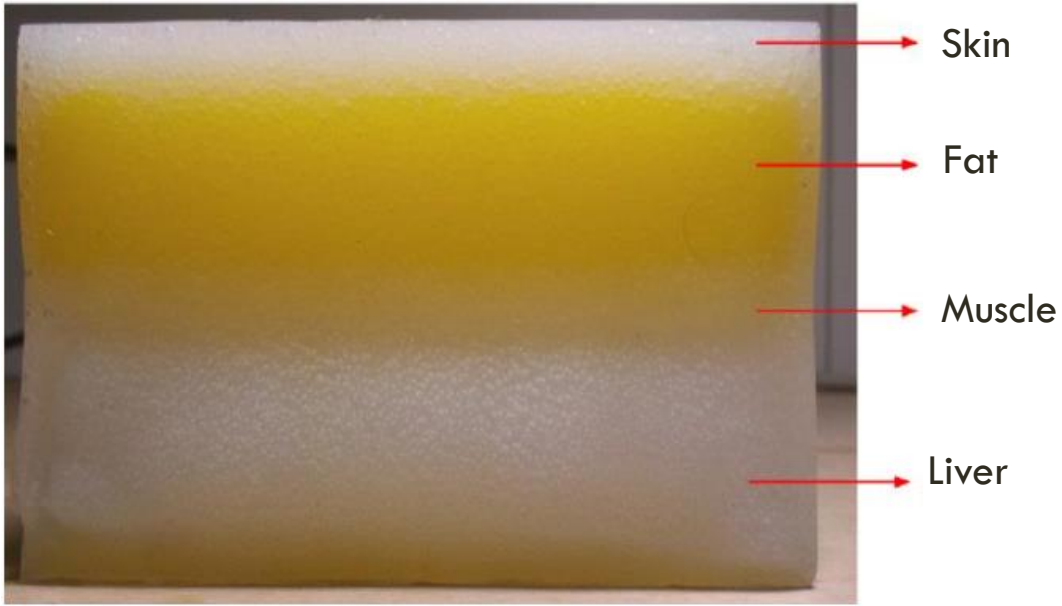
II - NEEDLE-TISSUE INTERACTION

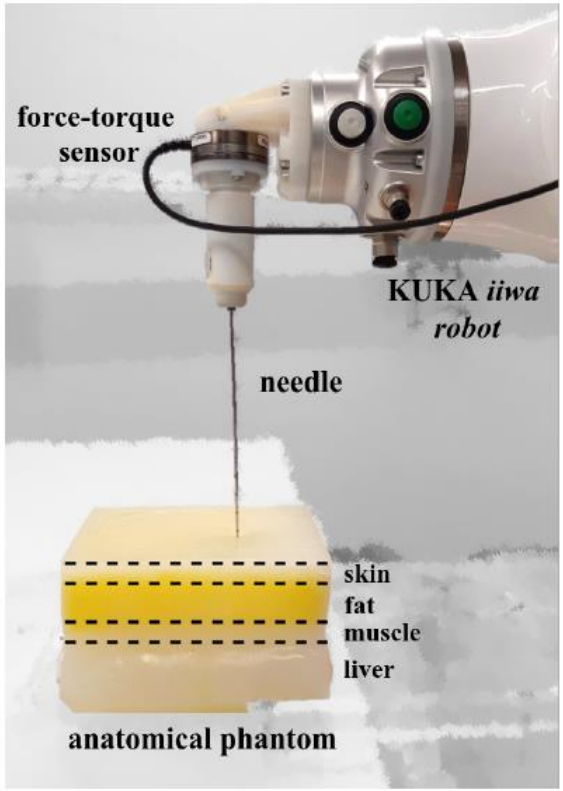
- FEM model already implemeted [7] : needle discretized into several beams.
- Before and during puncture : Unilateral constraint
  - Check if contact before puncture
  - Create contact constraint during puncture
- After penetration : Bilateral constraint (lateral + friction)
  - Guide the needle through its path, prevent lateral motion
  - A new constraint is added at every ConstraintDist



III — MY WORK

III - FORCES DURING NEEDLE INSERTION

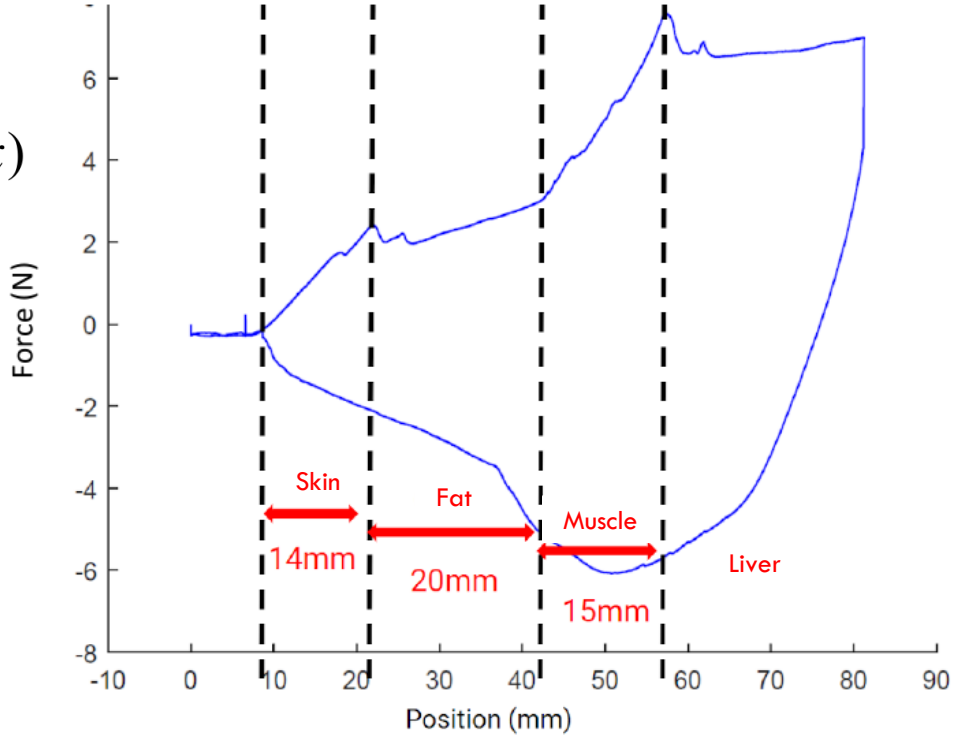




III - FORCES DURING NEEDLE INSERTION

$$f_{needle}(x) = f_{stiffness}(x) + f_{friction}(x) + f_{cutting}(x)$$

- Before and during puncture :
  Stiffness → unilateral constraint
- After puncture :
  Friction + cutting → Bilateral constraint
- Need position + force + velocity
  to estimate force using KV



III - LAYER CHANGE DETECTION

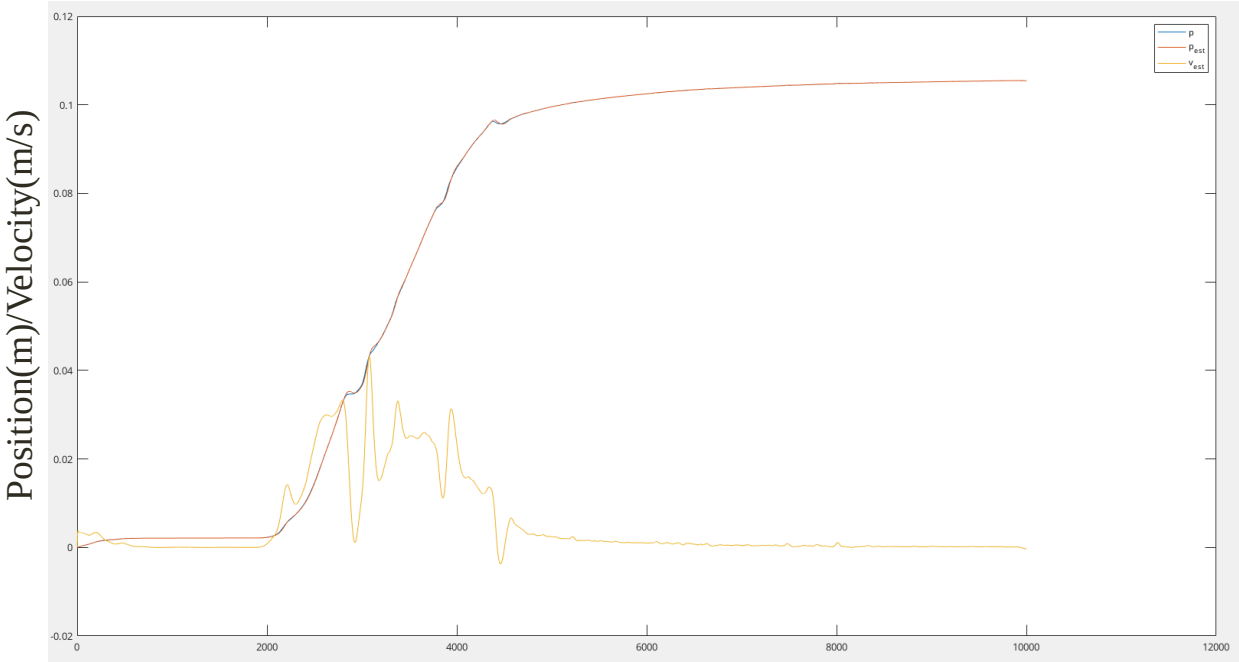
- Kalman filter used to estimate velocity from needle position

- $$\begin{aligned} p_{k+1} &= p_k + Tv_k + \frac{T^2}{2}\gamma_k \\ v_{k+1} &= v_k + T\gamma_k \end{aligned}$$

- $$\begin{aligned} x_{k+1} &= A_k x_k + G_k \gamma_k \\ y_k &= C_k x_k + w_k \end{aligned}$$

$$x_k = (p_k \ v_k)^T \quad A_k = \begin{pmatrix} 1 & T \\ 0 & 1 \end{pmatrix}$$

$$G_k = \begin{pmatrix} \frac{T^2}{2} \\ T \end{pmatrix} \qquad C_k = (1 \ 0)$$



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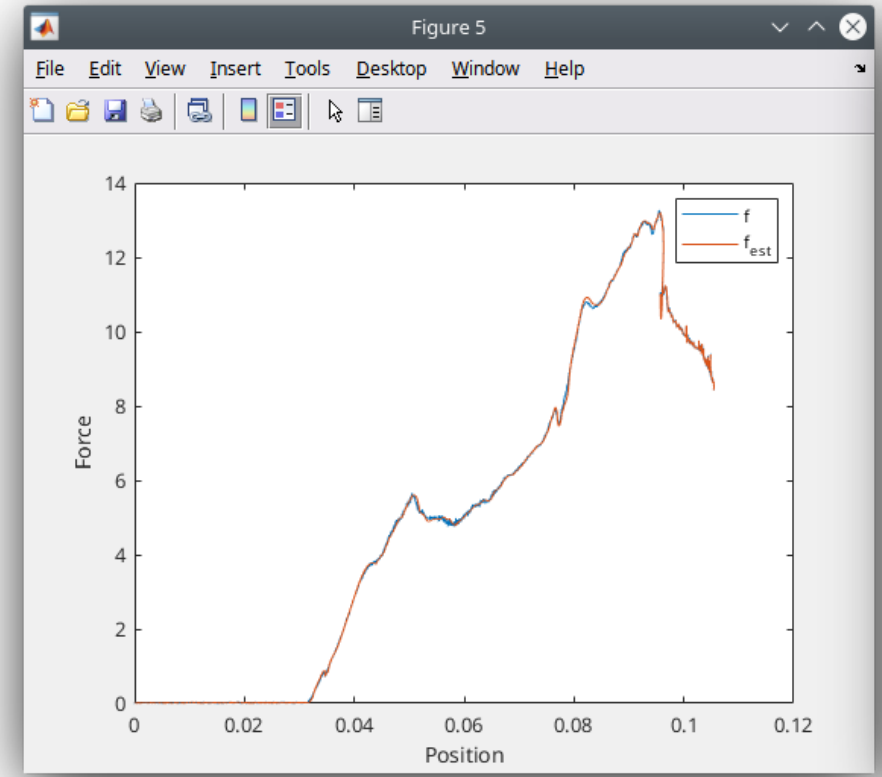
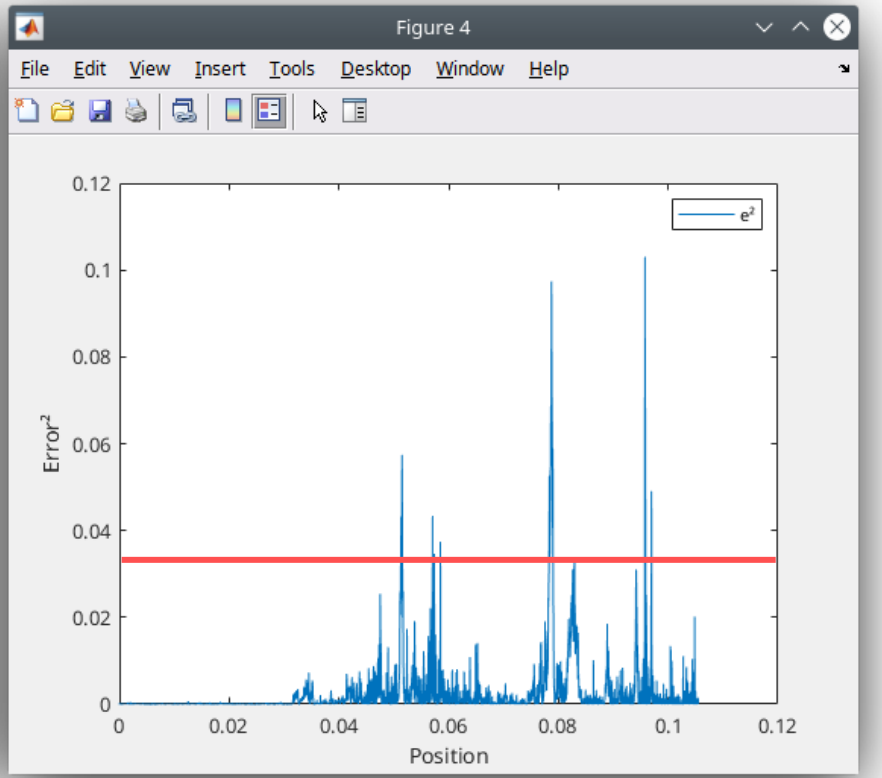
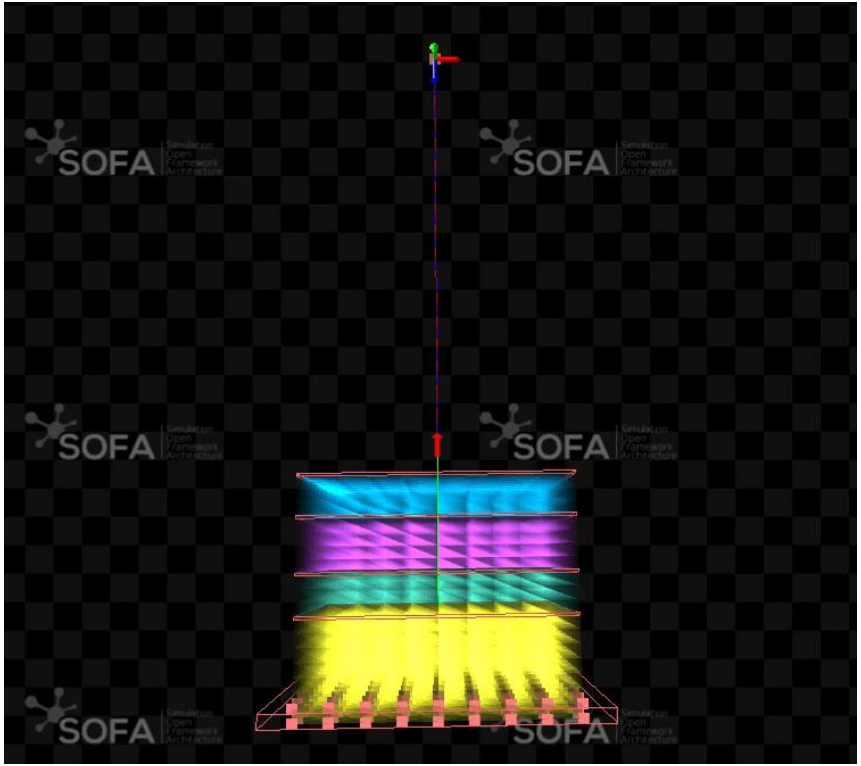
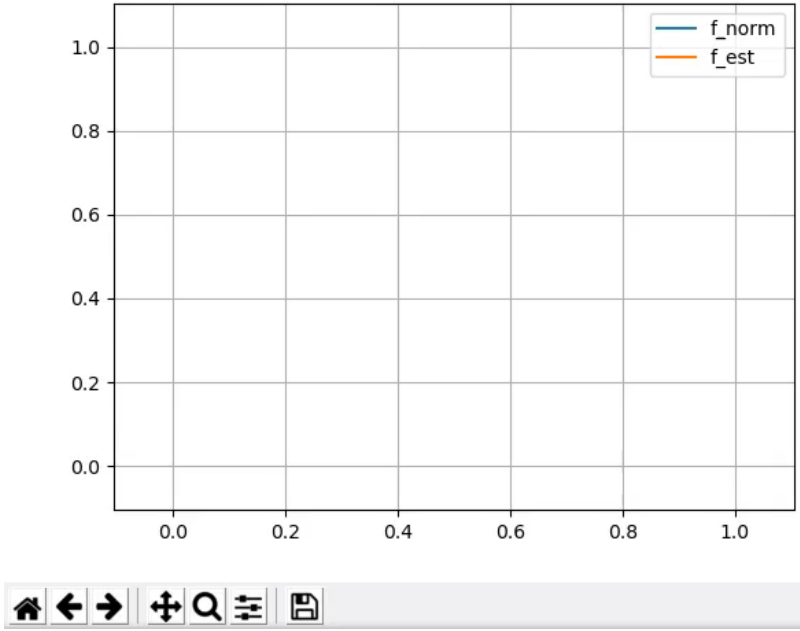




III - HETEROGENEOUS GEL





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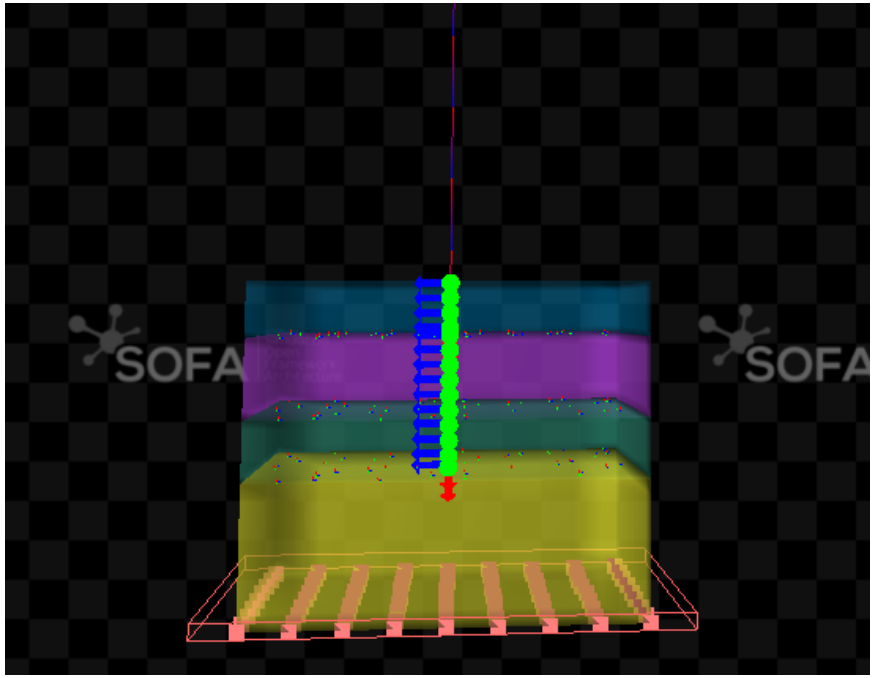
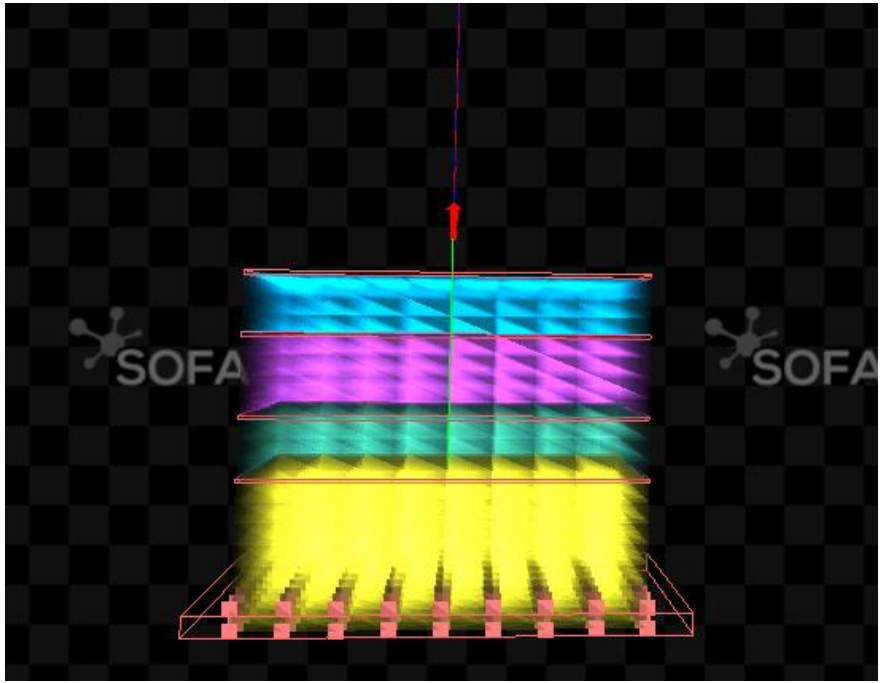
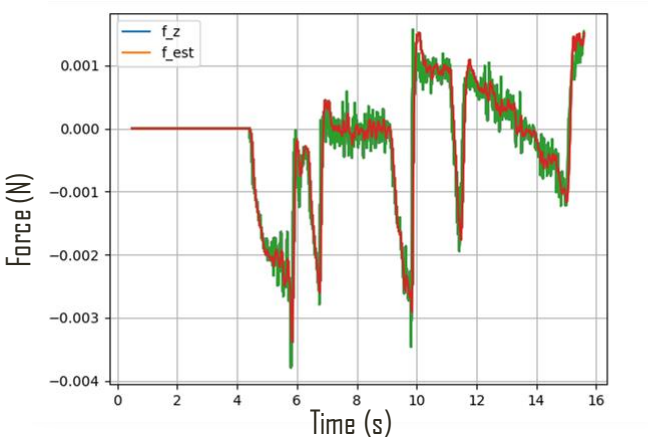


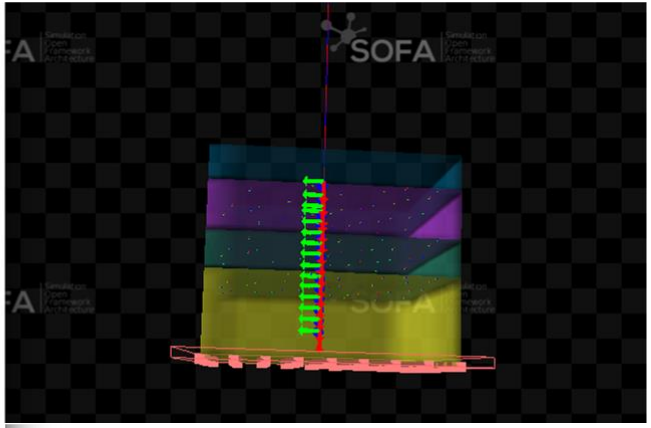
+ 1000 constraints
4 FEM

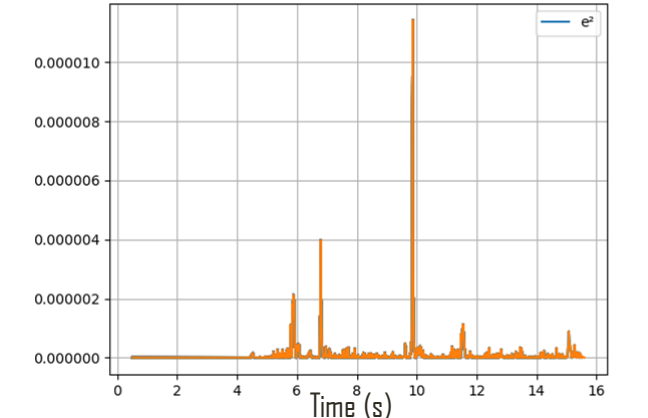


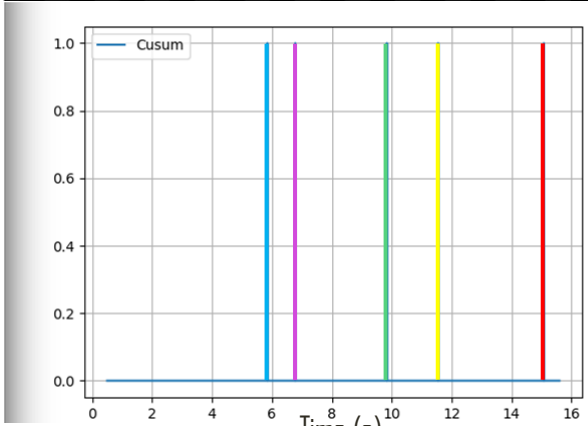
~ 50 constraints
1 FEM

III - LAYER CHANGE DETECTION









III – LAYER CHANGE DETECTION

ConstraintDist	Skin puncture detection	Fat puncture detection	Muscle puncture detection	Liver puncture detection
5mm	Ground truth + 30ms	GT + 50ms	GT + 40ms	GT + 60ms
10mm	GT + 30ms	GT + 30ms	GT + 40ms	GT + 50ms
20mm	GT + 30ms	GT + 50ms	GT + 30ms	GT + 50ms

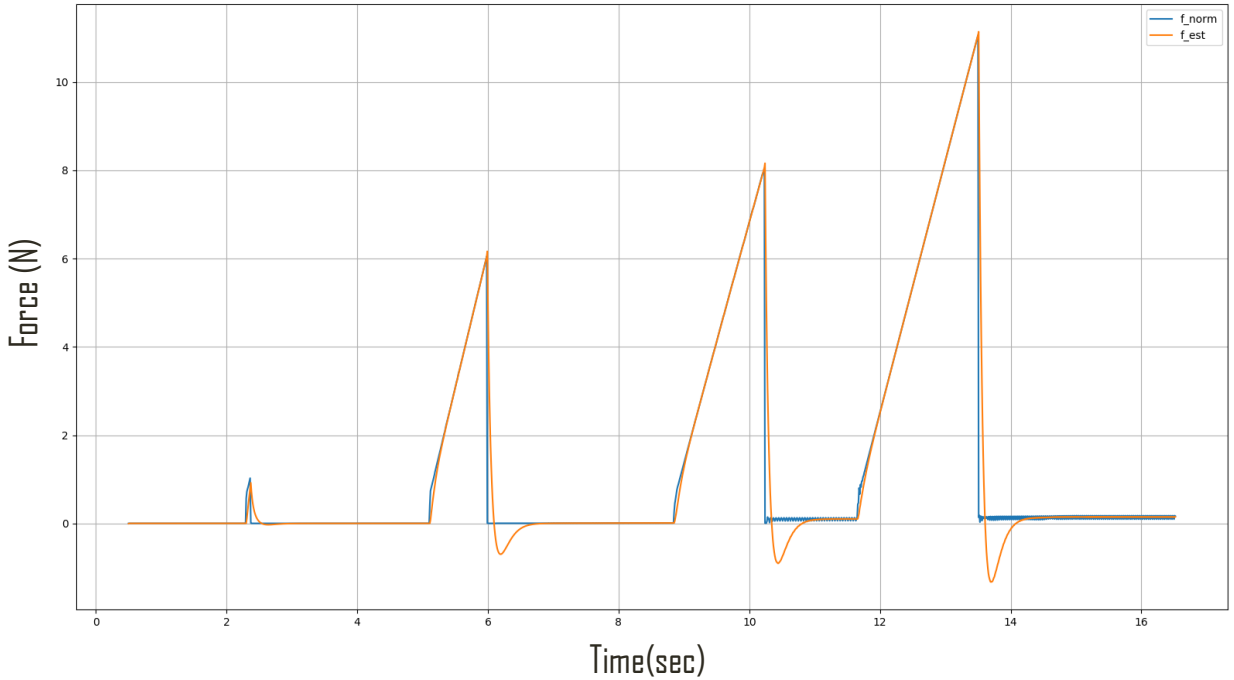
dt = 10 ms

On average +50ms → 5 time steps

IV – FUTURE PERSPECTIVES

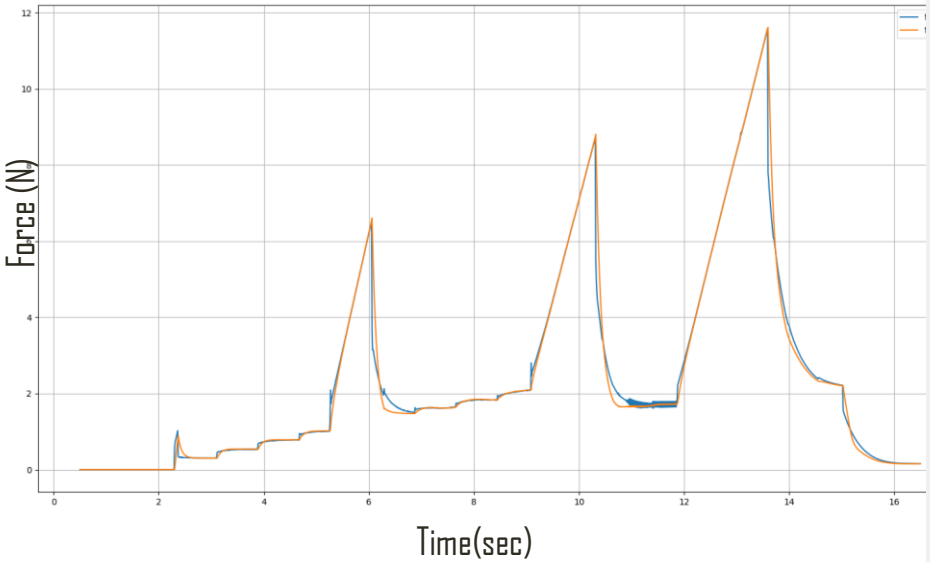
IV - MEASUREMENT OF THE BASE FORCE

- No friction
- Stiffness force only
- Possibility to set
  -Penetration Force
  -ConstraintDist

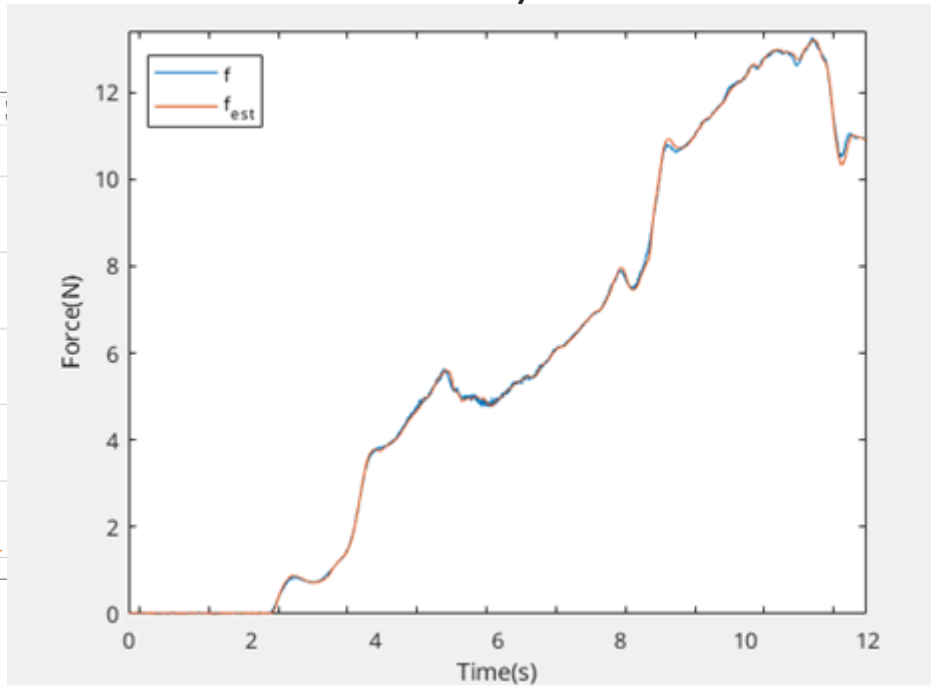


IV - FRICTION

Simulation

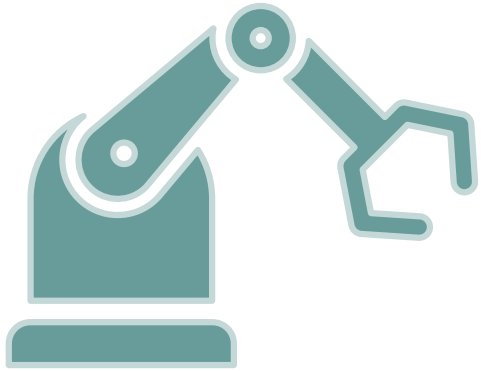


Reality



IV – NEXT STEPS

- Better simulate friction
- Obtain a time non-dependent and ConstraintDist non-dependent model
- Test the layer change detection algorithm with a more realistic model
- Online estimation of friction force applied to the needle during insertion



CONCLUSION

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- Layer change detection
- Needle Insertion Modelling
- Friction coefficient estimation
- Event-driven simulation

REFERENCES

[1] A. M. Okamura, C. Simone, and M. D. O'Leary, "Force modeling for needle insertion into soft tissue," IEEE Transactions on Biomedical Engineering, vol. 51, no. 10, pp. 1707–1716, 2004.

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