Autonomous endovascular navigation using reinforcement learning

Intern : Anne-Sarah DEBLY

Tutor : Stéphane COTIN

MIMESIS Team, INRIA

École d'ingénieurs Master IRIV
Télécom Physique Strasbourg

Tuesday, July 13th 2021

Summary

I – Context

a) Cardiac catherization

b) Navigation of an endovascular catheter

II – Reconstruction of the shape of the catheter

a) Optic fiber and Fiber Bragg Grating (FBG) principle

b) Modeling of the shape of the catheter

c) Implementation of the model in SOFA

III - Reinforcement learning for the autonomous navigation of a catheter

a) Reinforcement learning principle

b) Autonomous navigation of a catheter

Conclusion

I – Context

a) Cardiac catherization

b) Navigation of an endovascular catheter

II – Reconstruction of the shape of the catheter

a) Optic fiber and Fiber Bragg Grating (FBG) principle

b) Modeling of the shape of the catheter

c) Implementation of the model in SOFA

III - Reinforcement learning for the autonomous navigation of a catheter

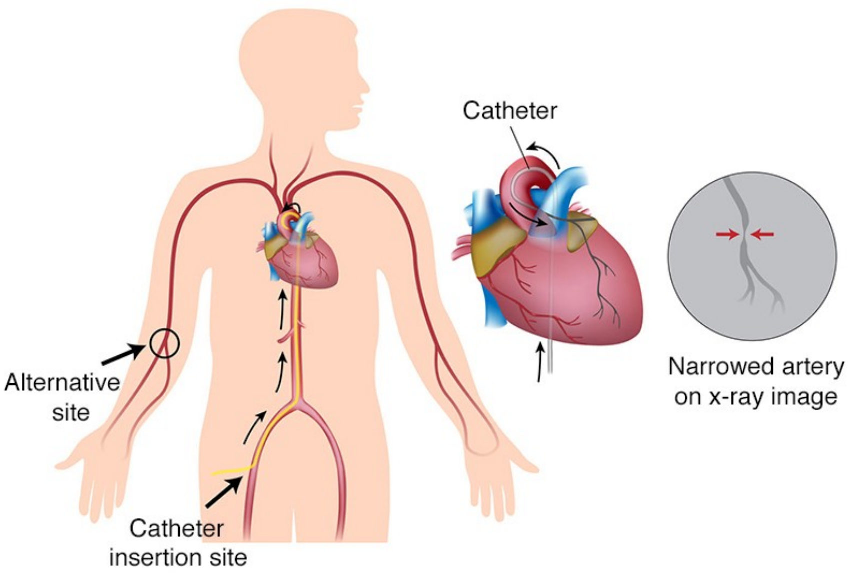
a) Reinforcement learning principle

b) Autonomous navigation of a catheter

Conclusion

I - Context

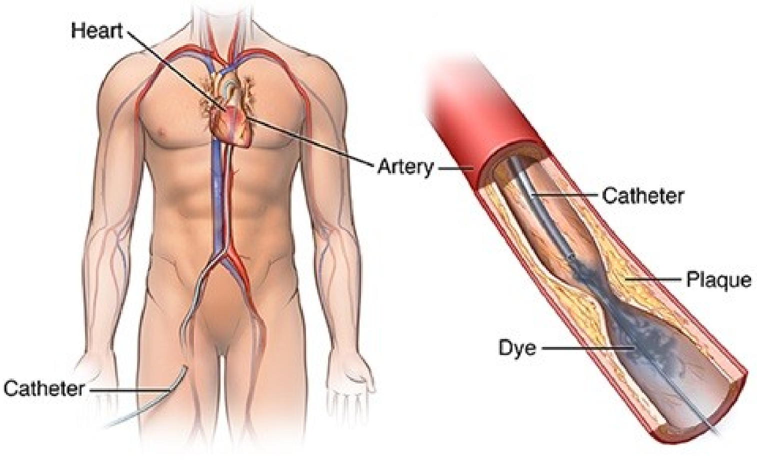
a) Cardiac catherization

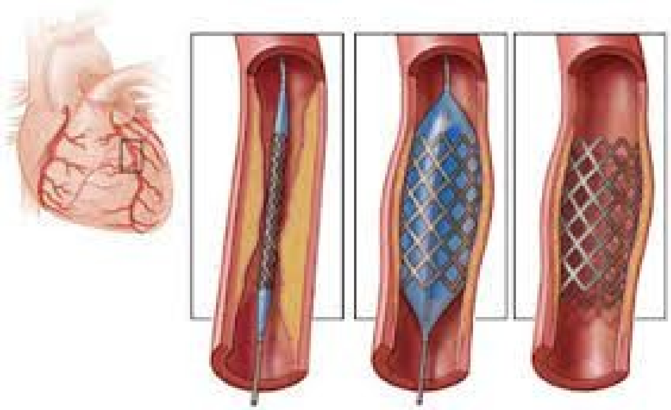


- Minimaly invasive procedure are used to treat cardiac diseases and blood vessel problems
- Insertion of a catheter into a blood vessel from the insertion site to the heart
- Procedure based on fluoroscopy to visualize the catheter and the vessels in real-time

I - Context

a) Cardiac catherization





- Main interest : treat plaque, heart failure or congenital heart disease
- Inject contrast to check blood flood and follow the catheter

I - Context

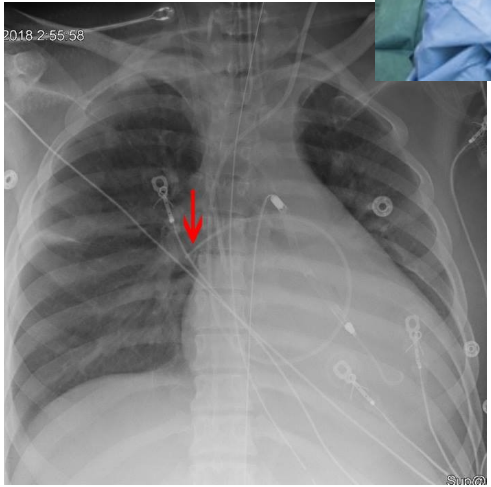
b) Navigation of an endovascular catheter

Problems with endovascular procedure:

- No tactile feedback
- Non-direct visual feedback with X ray images and constrast in vessels

⇒ Hard to navigate in the vessel tree in 3D with only 2D images

⇒ High contrast dose to compensate the visualization



I – Context

a) Cardiac catherization

b) Navigation of an endovascular catheter

II – Reconstruction of the shape of the catheter

a) Optic fiber and Fiber Bragg Grating (FBG) principle

b) Modeling of the shape of the catheter

c) Implementation of the model in SOFA

III - Reinforcement learning for the autonomous navigation of a catheter

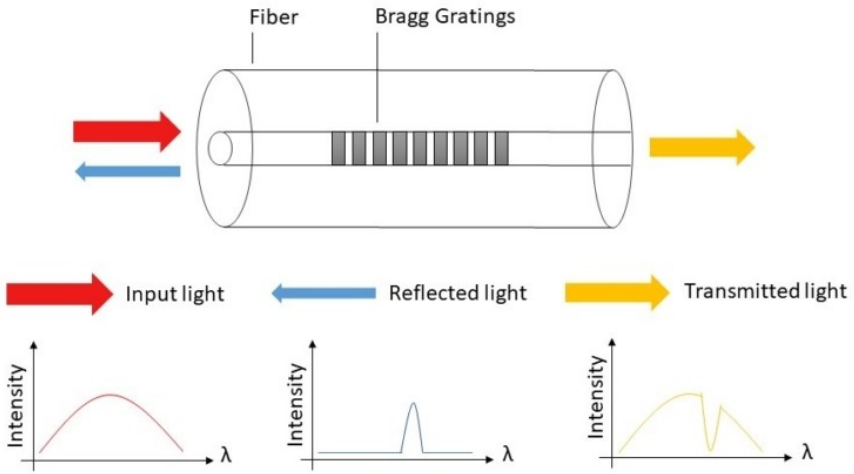
a) Reinforcement learning principle

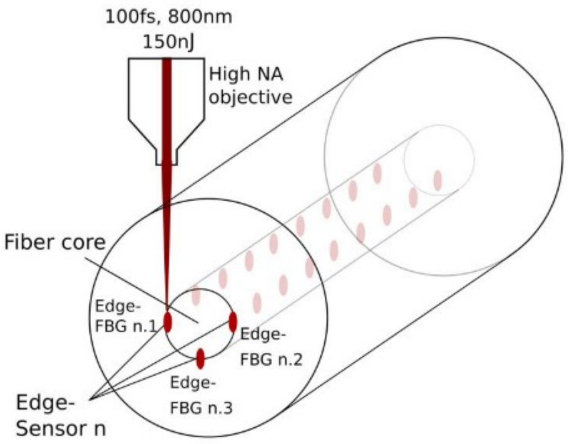
b) Autonomous navigation of a catheter

Conclusion

II – Reconstruction of the shape of the catheter

a) Optic fiber and Fiber Bragg Grating (FBG) principle

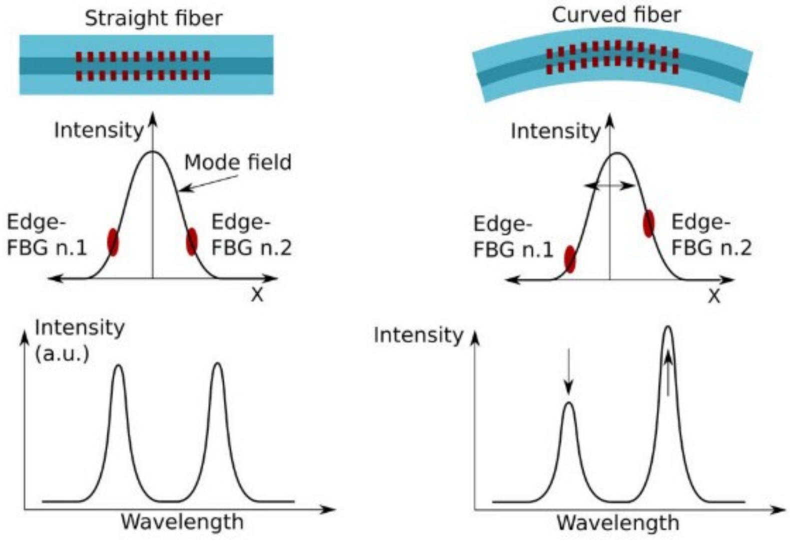




- edge sensors along the optic fiber
- 1 edge sensor = 3 edge FBG

II – Reconstruction of the shape of the catheter

a) Optic fiber and Fiber Bragg Grating (FBG) principle



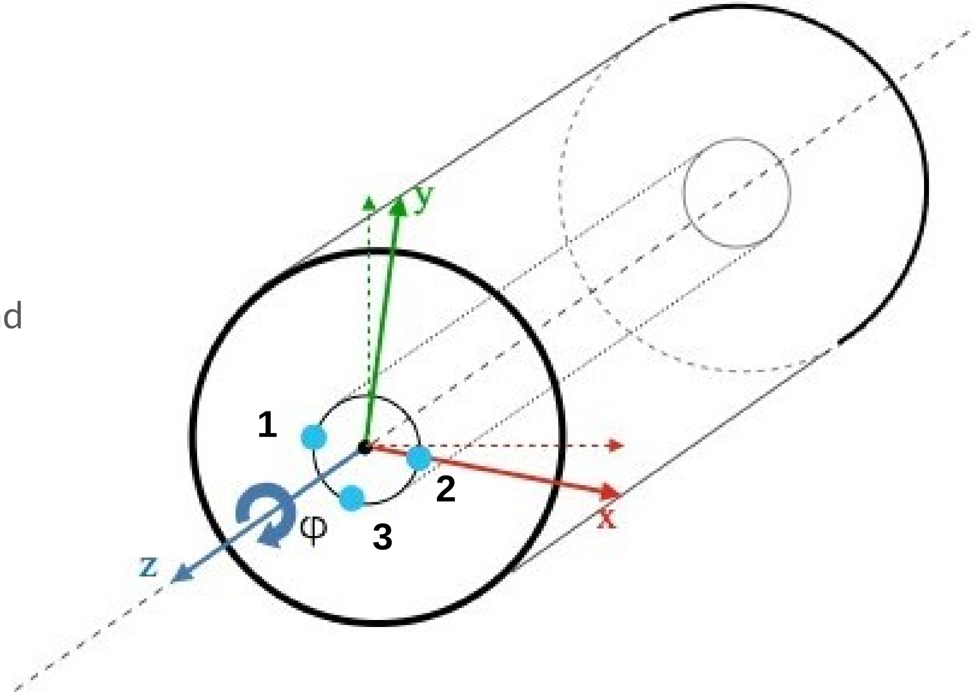
- The shape of the fiber at an edge sensor modify the intensity of the wavelength at this point

=> Use of this information to determine the shape of the catheter

II – Reconstruction of the shape of the catheter

a) Optic fiber and Fiber Bragg Grating (FBG) principle

- 3 edge FBG for each edge sensor sufficient for the reconstruction
- Edge-FBG 1 and 2 : rotation around axis z
  => angle Phi
- Edge-FBG 1 (or 2) and 3 : rotation around axis x
  => radius of curvature R

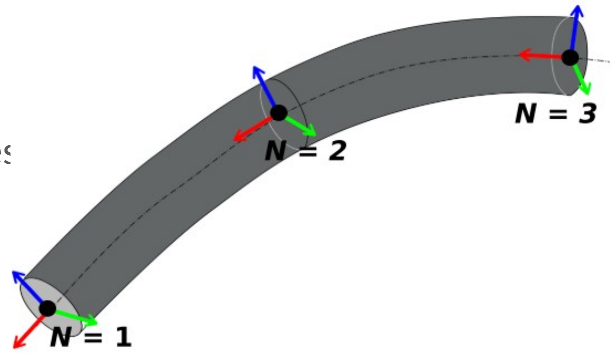


II – Reconstruction of the shape of the catheter

b) Modeling of the shape of the catheter

Representation adapted to our problem

- R and Phi -> rotations -> need frames in the representation
- Model adapted to the geometry of the catheter
- Mechanical interpolation between the nodes



⇒ Beam model : catheter represented as a succession of nodes linked by beams

⇒ adapted to long and thin deformable objects

⇒ representation with frames / 6dof (3 for the position, 3 for the rotation)

⇒ Mechanical interpolation

⇒ Parameters : radius, Poisson’s coeffient, Young modulus

II – Reconstruction of the shape of the catheter

b) Modeling of the shape of the catheter

- Equation of the beam model with the 2nd law of Newton:

$M\ddot{x} = f$ with $f = F + C\dot{x} + Kx$

=> $\boldsymbol{M\ddot{x} - C\dot{x} - Kx = F}$

M : mass matrix
F : external forces
C : damping matrix
K : stiffness matrix

  - $C = \frac{df}{dv} = \alpha M + \beta K$ with α the Rayleigh mass and β the Rayleigh stiffness
  - represents how the nodes are linked at the initial state :
  - $K = \frac{df}{dx}$ represents how the nodes are linked at the initial state : $\boldsymbol{-Kx = F}$

II – Reconstruction of the shape of the catheter

b) Modeling of the shape of the catheter

- Integration scheme

Integration scheme

$M\ddot{x} = f$ => $M\,\Delta v = dt\, f(x,\dot{x})$

=>

Taylor dv : $f(x,\dot{x}) = f\big(x(t+dt), \dot{x}(t+dt)\big)$

Taylor dv :

And $\Delta x = dt(v(t) + \Delta v)$

And

=> $M\,\Delta v = dt\left(f + dt\,\frac{df}{dx}v + dt\,\frac{df}{dx}\Delta v + \frac{df}{dv}\Delta v \right)$

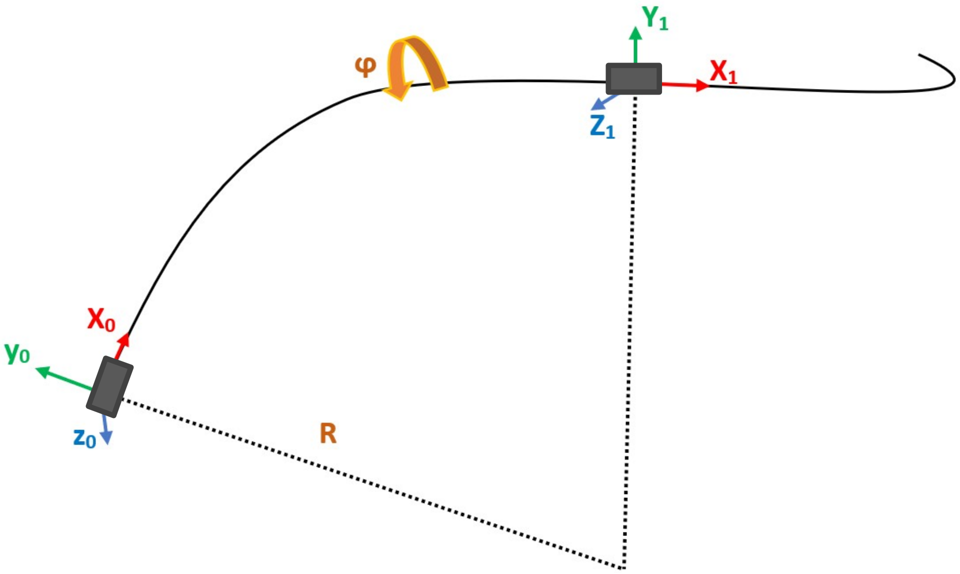
$$\left(M - dt\,\frac{df}{dv} - dt^2\,\frac{df}{dx}\right)\Delta v = dt\left(f + dt\,\frac{df}{dx}\,v\right)$$

Paramètres dans notre cas : E grand car cathéter inextensible, longueur centrale constante (indéformable)

$\mathbb{C}$ K

II – Reconstruction of the shape of the catheter

c) Implementation of the model on SOFA



Definition of FBG sensors as frames

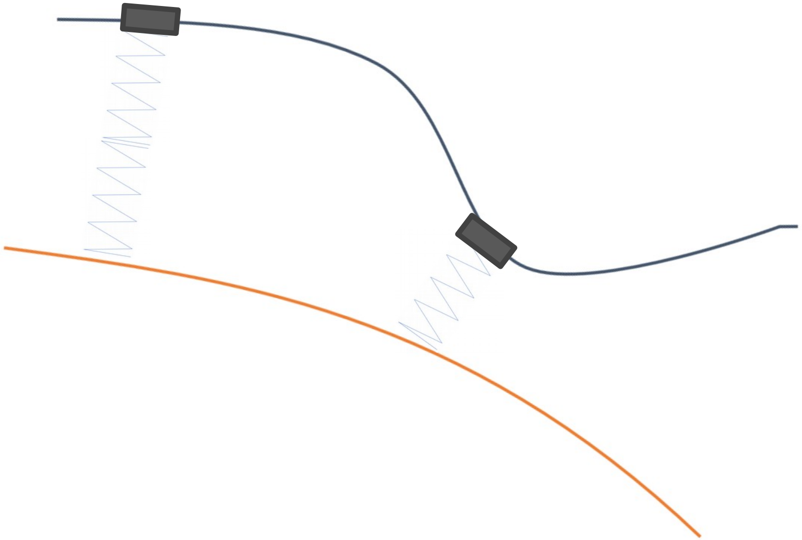
- SOFA : beam along axis x
- Phi : rotation around x
- R : transformation on a angle of rotation around z

=> Modeling of a beam between each frame with the right orientation of the frame

II – Reconstruction of the shape of the catheter

c) Implementation of the model on SOFA

RestShapeSpringsForceField



- Use springs to impose forces between the actual shape and the target
- Impose constraints as penalties
- Goal : minimize forces between each frames of the two shapes => reach the target shape

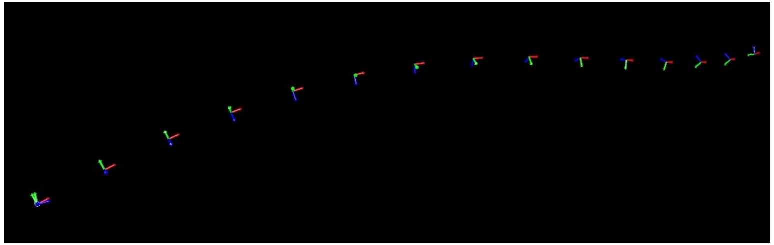
II – Reconstruction of the shape of the catheter

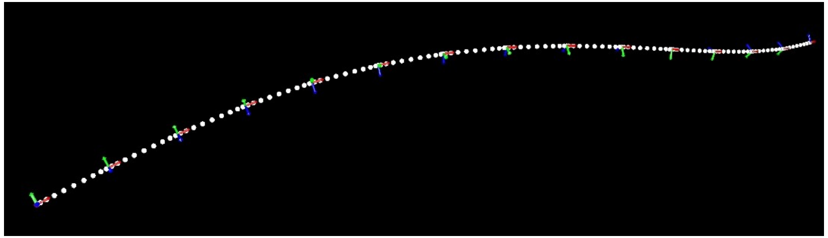
c) Implementation of the model on SOFA

BeamLinear Mapping

- Used to link the oriented nodes between them => reconstruction of the shape of the catheter

- Define little spheres as a visual model to see the beam model between each node





II – Reconstruction of the shape of the catheter

c) Implementation of the model on SOFA

FiSens BragSens

- FiSens software to record data from the edge FBG

Data transmission

FiSens FBG 3D Shape

- FiSens software to transform data into R and Phi

Data transmission by UDPStream

Modeling of the catheter

- Use of R and Phi data in real time
- Modeling with SOFA

II – Reconstruction of the shape of the catheter

c) Implementation of the model on SOFA

- Demonstration of the reconstruction with 1 FBG sensor and a fixed point

I – Context

a) Cardiac catherization

b) Navigation of an endovascular catheter

II – Reconstruction of the shape of the catheter

a) Optic fiber and Fiber Bragg Grating (FBG) principle

b) Modeling of the shape of the catheter

c) Implementation of the model in SOFA

III - Reinforcement learning for the autonomous navigation of a catheter

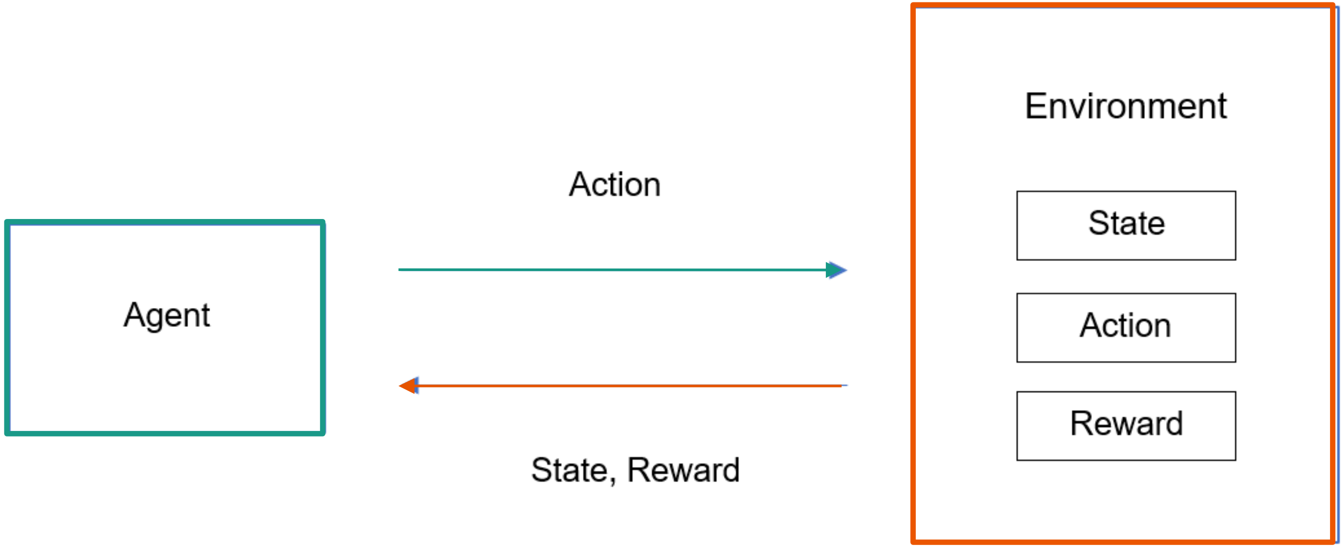
a) Reinforcement learning principle

b) Autonomous navigation of a catheter

Conclusion

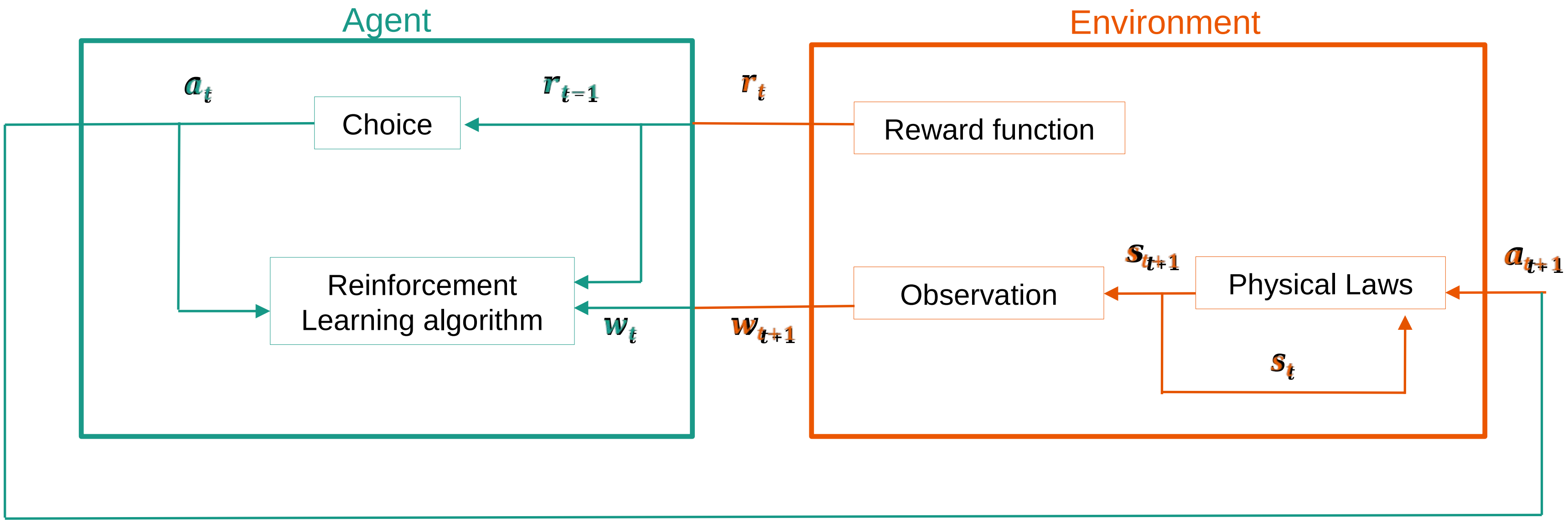
III – Reinforcement learning for the autonomous navigation of a catheter

a) Reinforcement learning principle



III – Reinforcement learning for the autonomous navigation of a catheter

b) Autonomous navigation of a catheter



III – Reinforcement learning for the autonomous navigation of a catheter

b) Autonomous navigation of a catheter

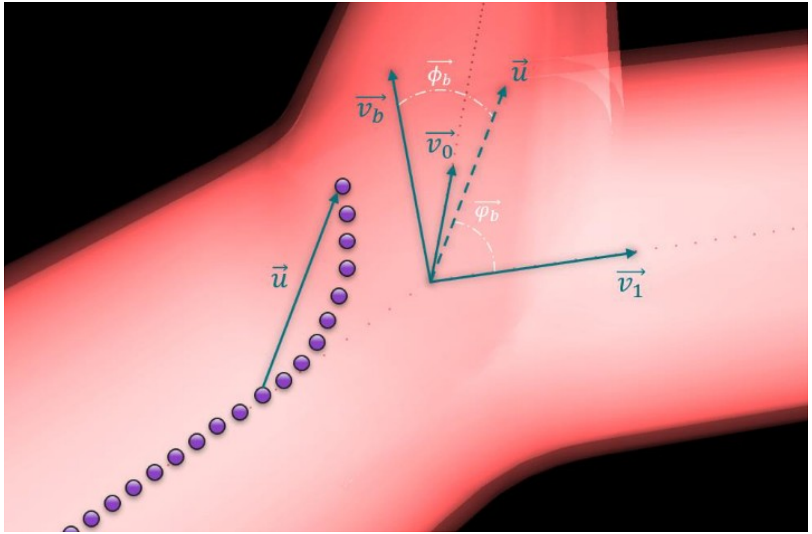
Input

Physical laws
Set of possible movements

DRL algorithm

Output

Reward according the impact of the command
Command to be done by the robot

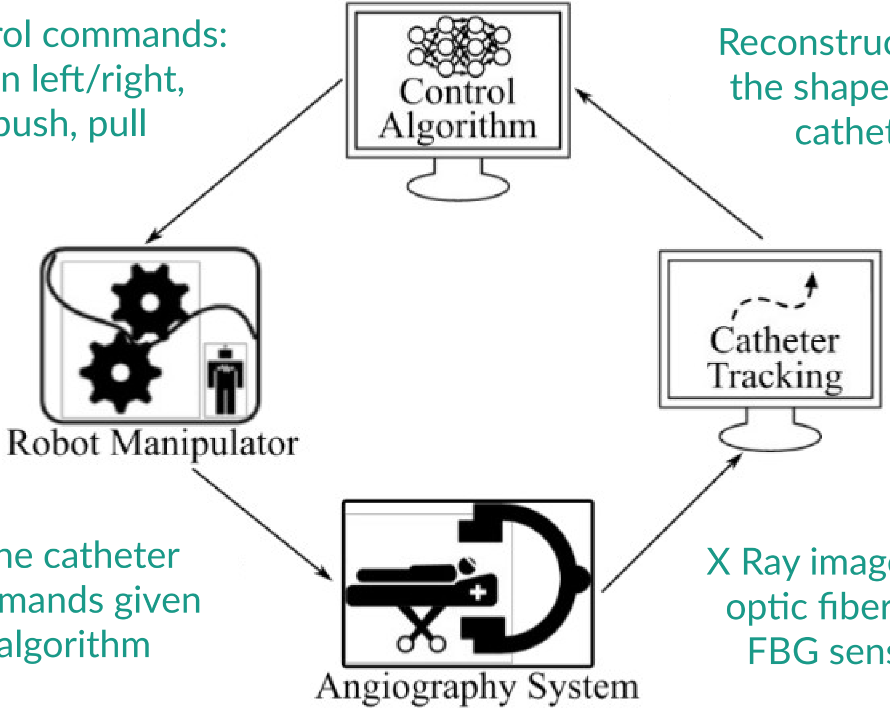


III – Reinforcement learning for the autonomous navigation of a catheter

b) Autonomous navigation of a catheter

Control commands:
turn left/right,
push, pull

Reconstruction of
the shape of the
catheter



Control of the catheter
with the commands given
by the RL algorithm

X Ray images and
optic fiber with
FBG sensors

I – Context

a) Cardiac catherization

b) Navigation of an endovascular catheter

II – Reconstruction of the shape of the catheter

a) Optic fiber and Fiber Bragg Grating (FBG) principle

b) Modeling of the shape of the catheter

c) Implementation of the model in SOFA

III - Reinforcement learning for the autonomous navigation of a catheter

a) Reinforcement learning principle

b) Autonomous navigation of a catheter

Conclusion

Conclusion

Conclusion

- Catheter shape reconstructed thanks to FBG sensors and SOFA modeling

=> Need to improve the model to follow better the movements of the catheter with several FBG sensors

- Deep Reinforcement Learning algorithm to implement, with Robin's internship as a working basis

Thank you for your attention