Robot Control for Magnetic Microswimmers

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Fréjus, Oct. 28, 2021

What is a robot ?

In fact, the term "robot" means different things to different people.

Even roboticists themselves have different notions about what is or isn't a robot.

And for most of us, science fiction has strongly influenced what we expect a robot to look like and be able to do.

So what makes a robot? Here's a definition that is neither too general nor too specific:

A robot is an autonomous machine capable of sensing its environment, carrying out computations to make decisions, and performing actions in the real world.

https://robots.ieee.org/learn/what-is-a-robot/

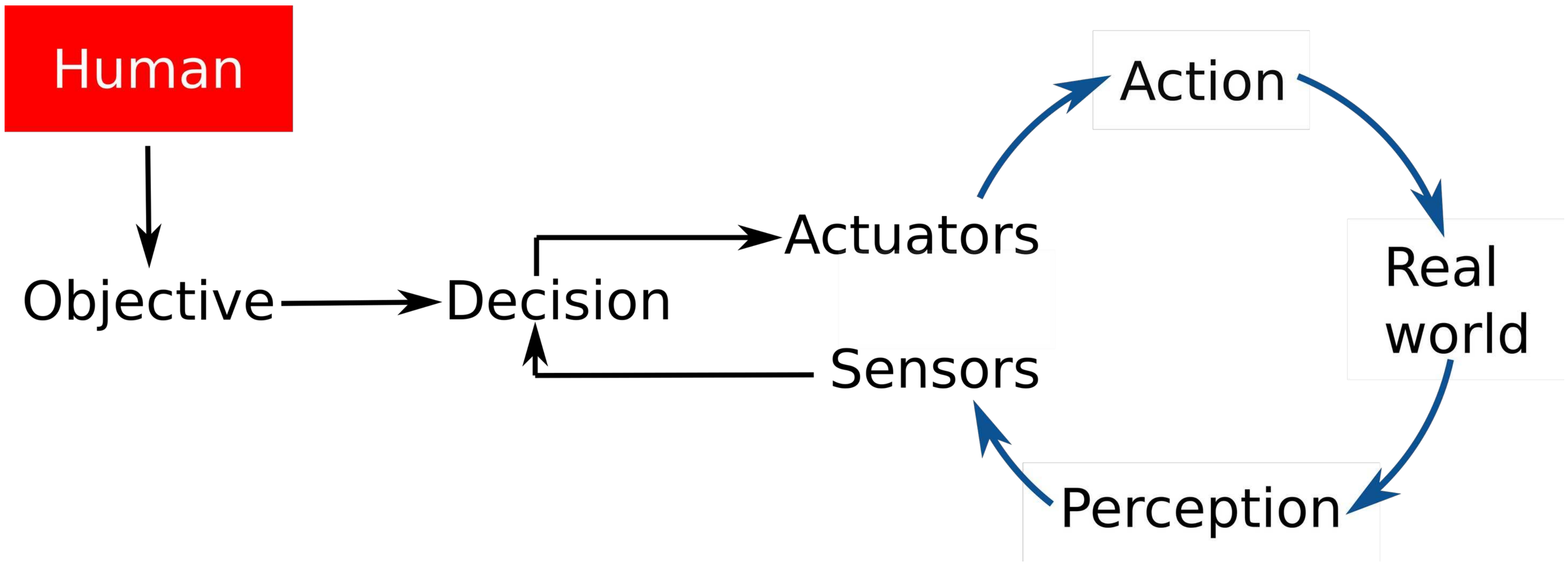
Beware of fuzzy and/or human-related vocabulary (cf. magic AI) !

A robot is an autonomous **machine** capable of **sensing its environment**, carrying out **programmed** computations, and **performing motion** in the real world to achieve **human-specified objectives**.

What is a robot ?

The perception/action cycle

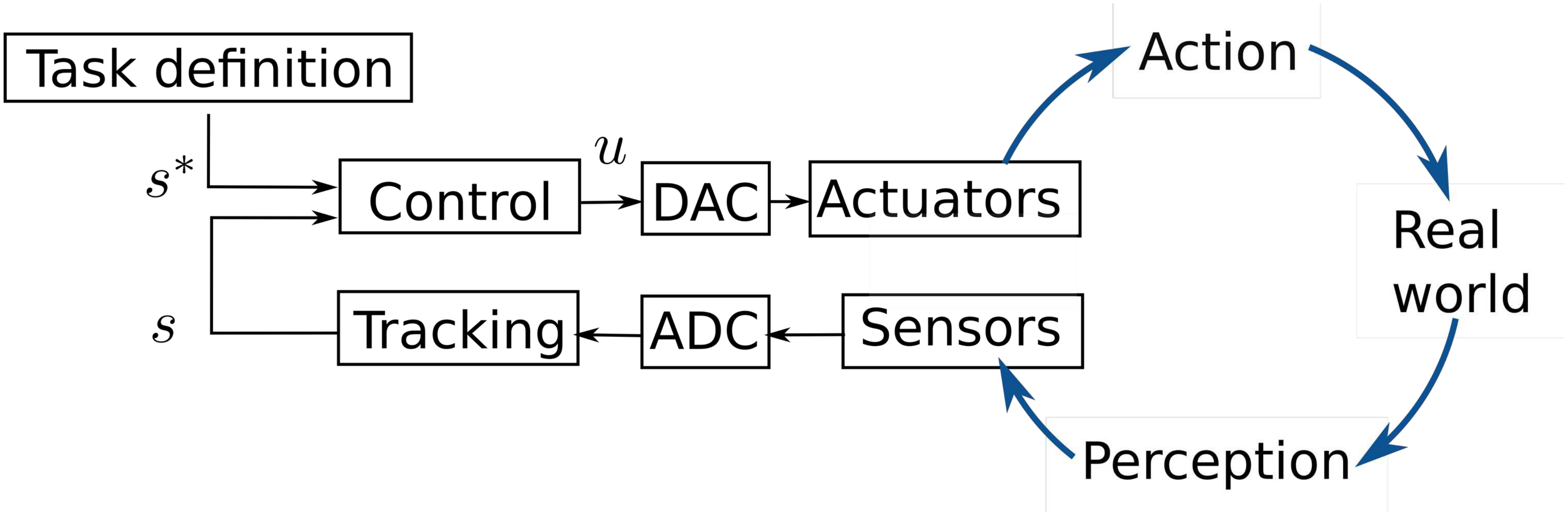
with a human-biased description of the robot structure



What is a robot ?

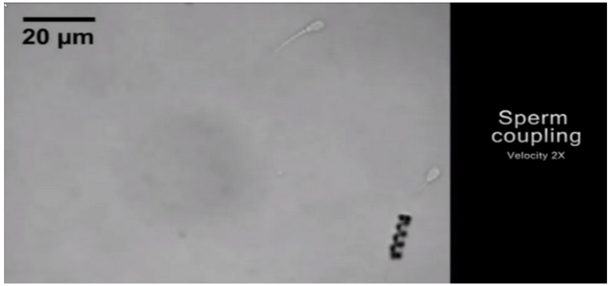
The perception/action cycle

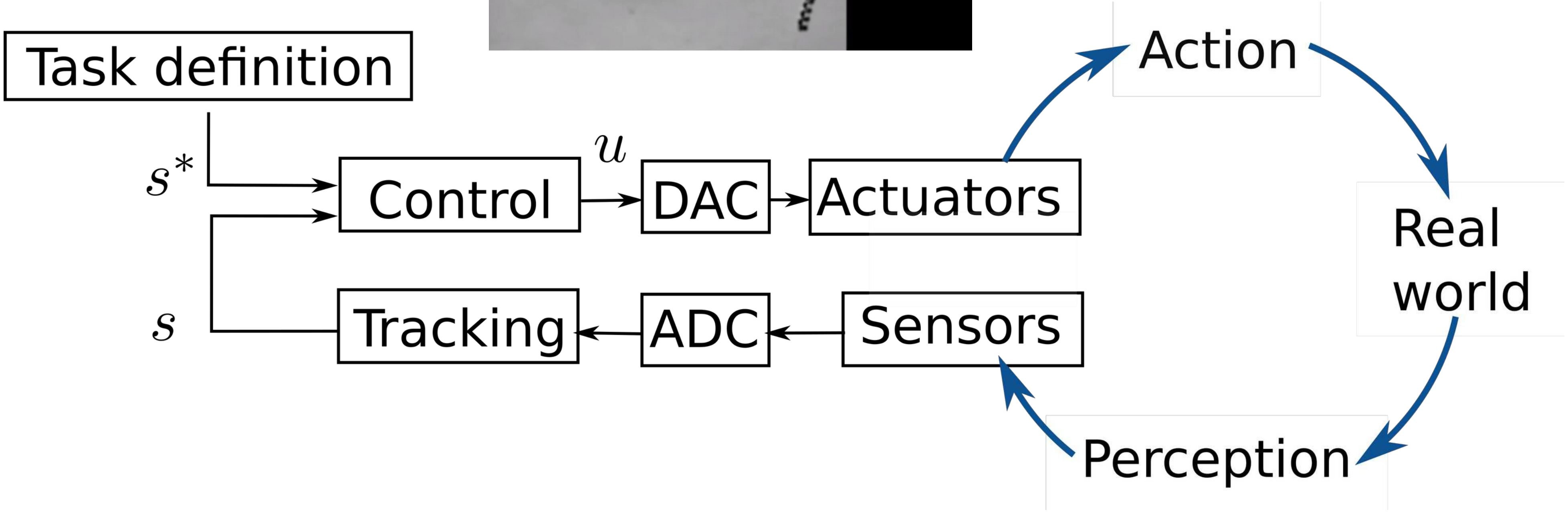
seen from the robot control standpoint



Is a magnetic microswimmer a robot ?

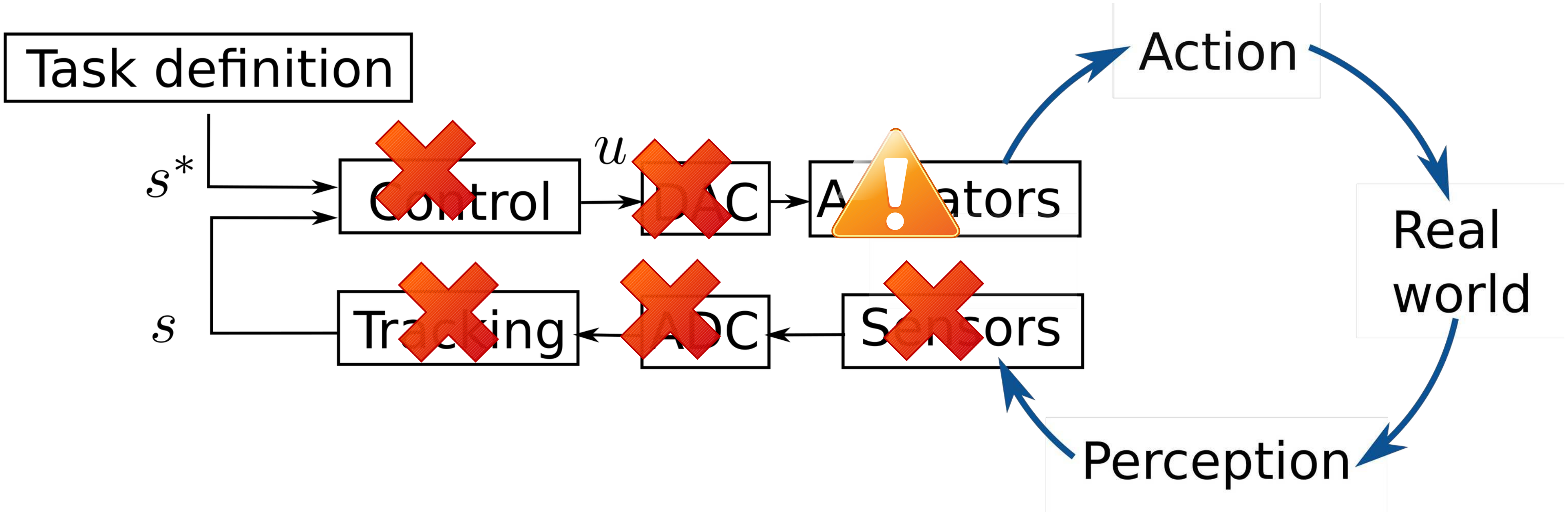
[Medina-Sanchez14]





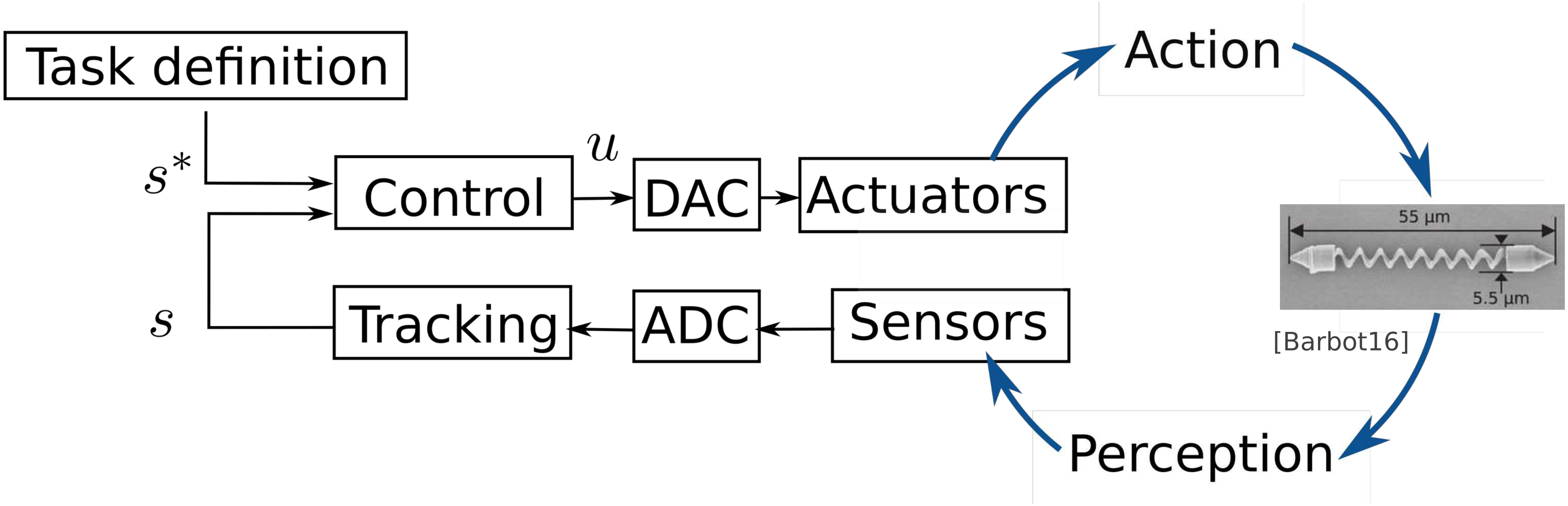
Is a magnetic microswimmer a robot ?

No

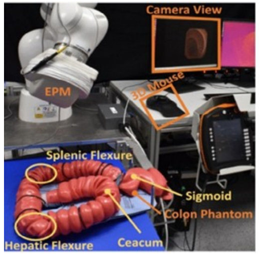


Is a magnetic microswimmer a robot ?

No, but a magnetic manipulation system is !



A short tour of magnetic manipulation systems



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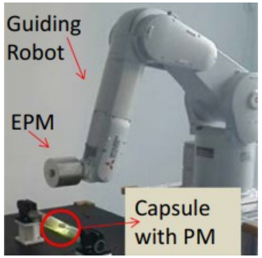
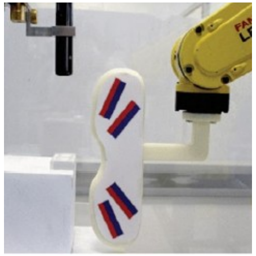


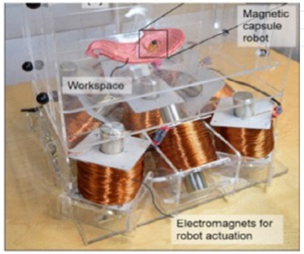
[Li18]



[Zarrouk19]

[Siemens/Olympus 12]

[Diller14]



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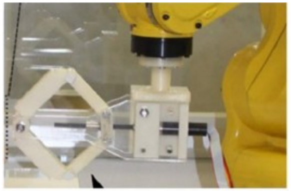
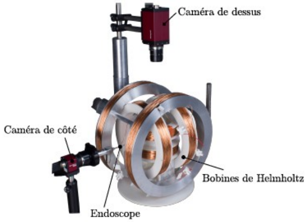


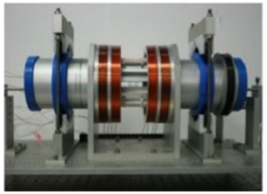
[Amokrane18]

[Liao16]

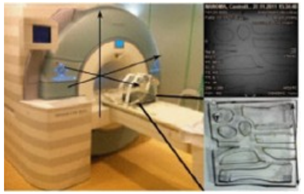
[Armacost07]



[Oulmas17]



[Choi10]

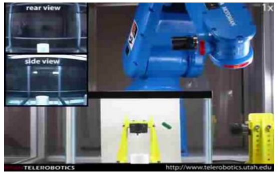


[Folio17]

[Ciutti 10]

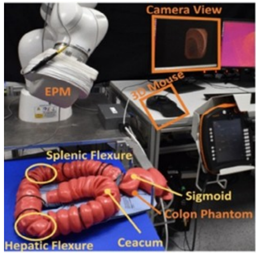
[Stereotaxis 10]

[Kummer 10]



[Mahoney 11]

A short tour of magnetic manipulation systems



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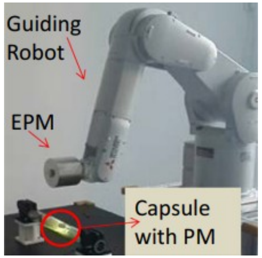

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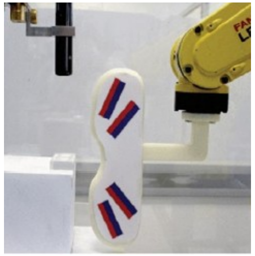
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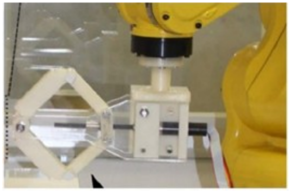
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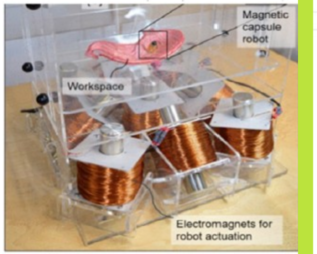

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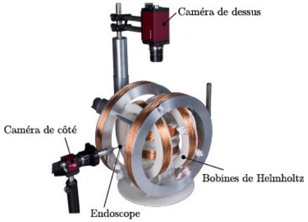

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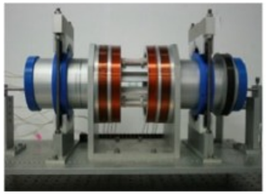
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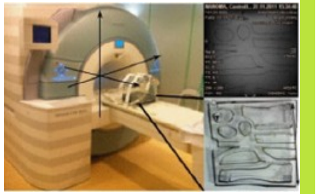
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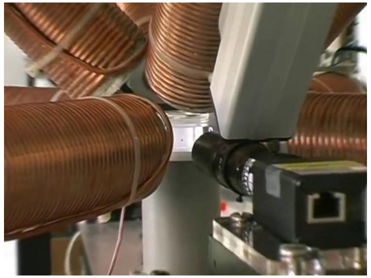
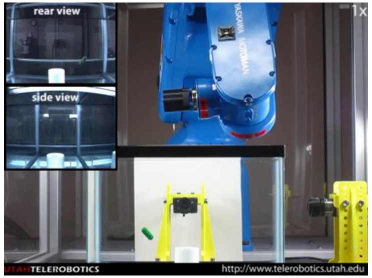

[Kummer 10]



[Mahoney 11]

Various kinds of magnetic manipulation systems

- **Mobile permanent magnets**
- **Static electromagnets**
- **Mobile electromagnets** [Véron 12]

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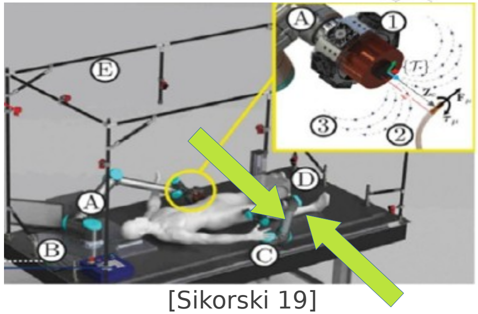

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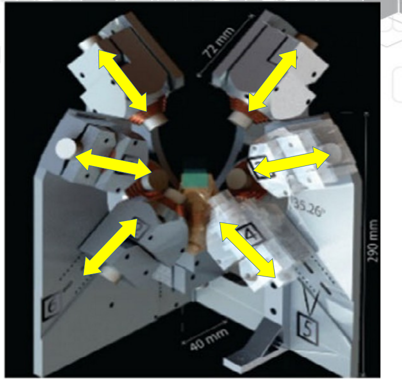

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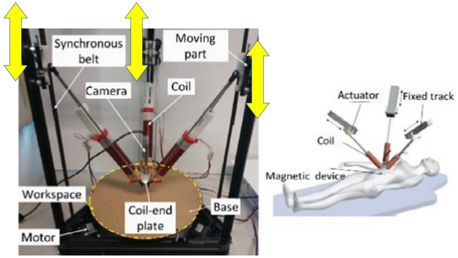

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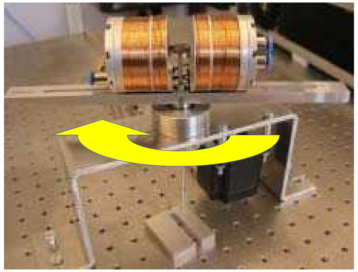

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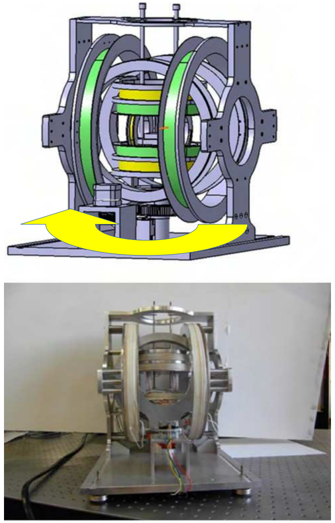

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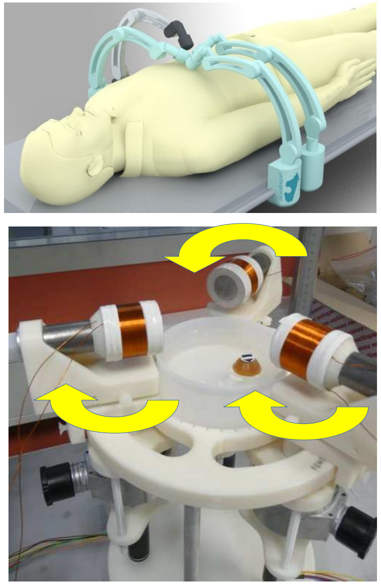

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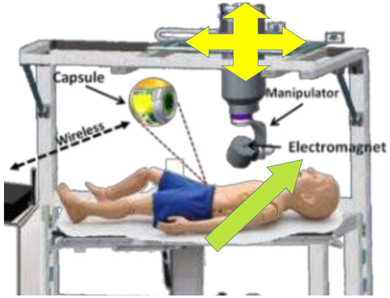
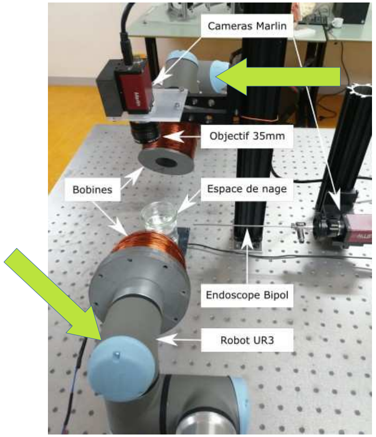


[Lucarini 15]

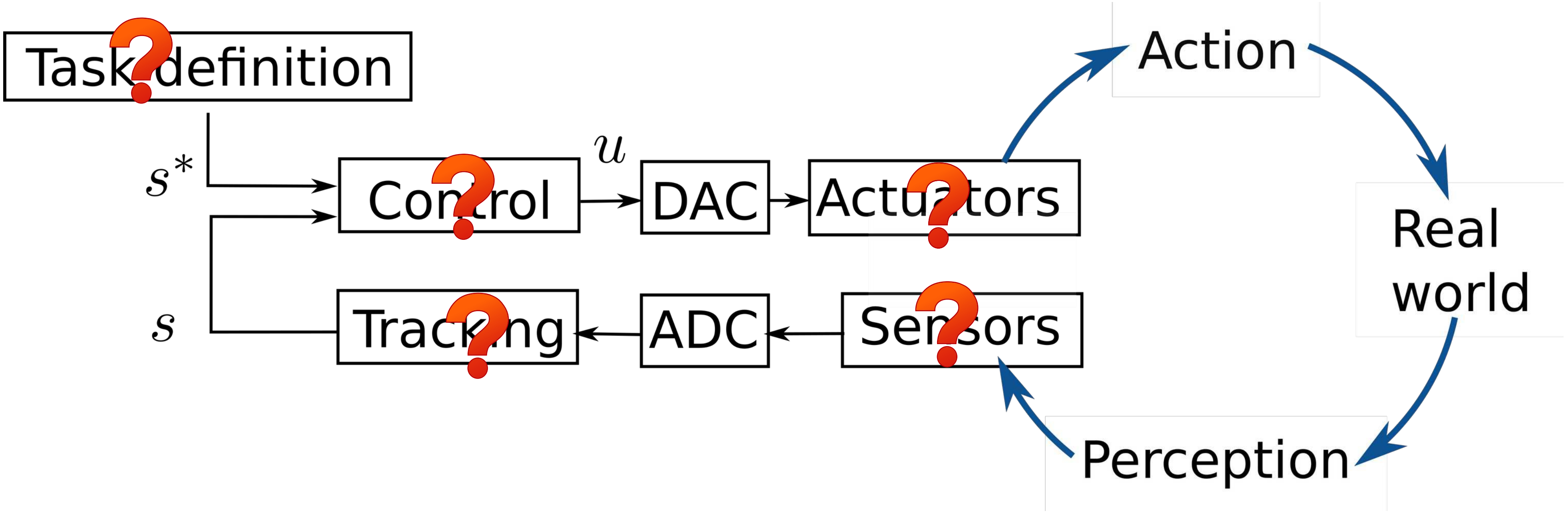


[Etiévant 21]

Pros and cons

Property	Static electromagnets	Mobile permanent magnets	Mobile electromagnets
Dexterity	⊕ complete	⊖ partial	⊕ complete
Source/object distance	⊖ long	⊕ short	⊕ short
Joule effect	⊖ strong	⊕ inert	⇝ reduced
Turn off the field	⊕ possible	⊖ impossible	⊕ possible
Stabilization	⊕ possible	⊖ unstable/difficult	⊕ possible
Control mode	⊕ simple	⊕ simple	⊕ redundant
Patient acceptance	⊖ weak	⊖ dangerous	⇝ improved

What is a magnetic manipulation system?



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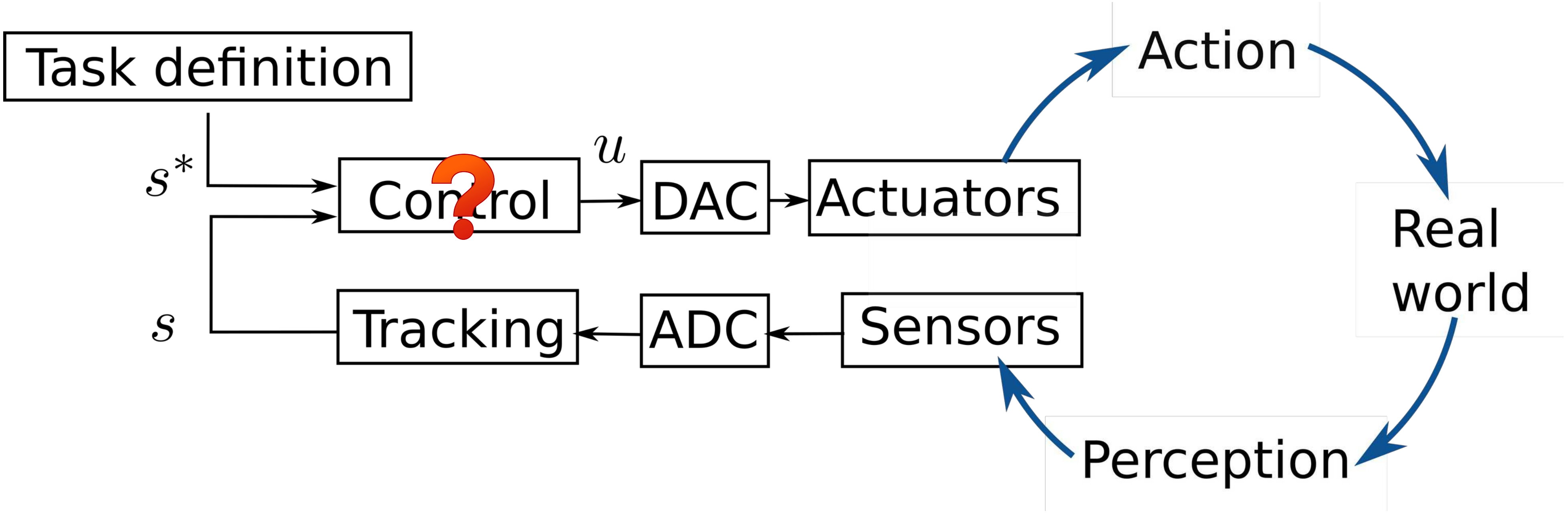
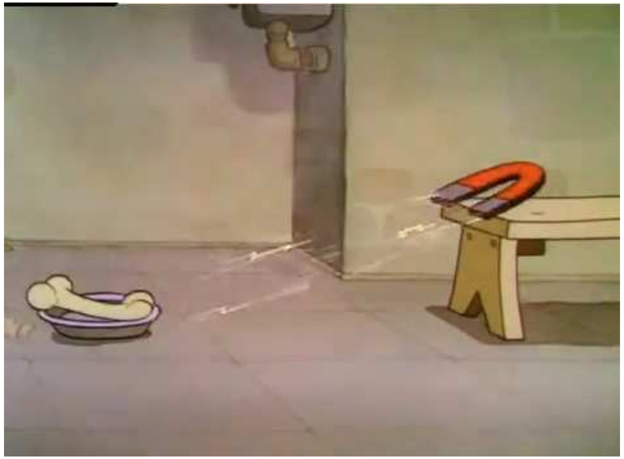
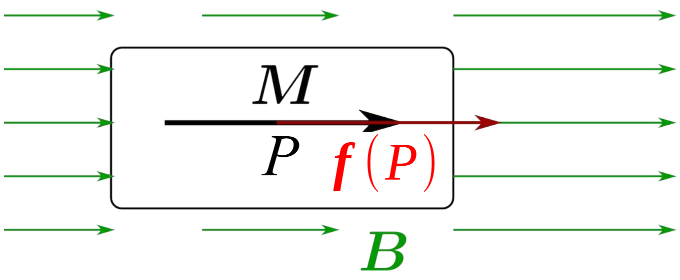


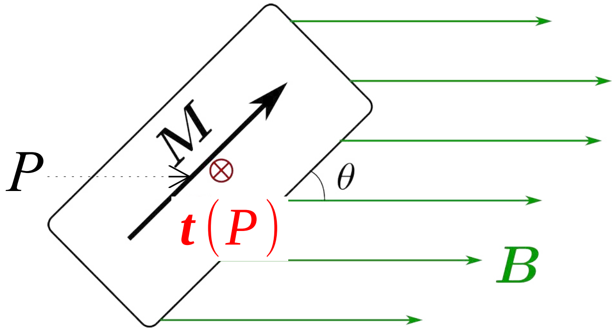
Control issues

- **Robot structure**
- Robot model
- Kinematic analysis
- Desired motion
- Control scheme

Magnetic efforts on a magnetic object







$$\boldsymbol{f}(P)=V\cdot\nabla(\boldsymbol{M}\cdot\boldsymbol{B}(P))$$

$$\boldsymbol{t}(P)=V\cdot\boldsymbol{M}\wedge\boldsymbol{B}(P)$$

Several actuation modes

- **Force and Torque (F/T)**
  - Dynamic equations
- **Force and Field (F/B)**
  - Higher dynamics in rotation then in translation : M (almost) always aligned with B, thus T=0
- **Field only (B)**
  - Uniform field $\rightarrow$ F = 0
  - Uniform field easy to produce : Helmholtz configuration
  - Force scales down poorly
- **Force only (F)**
  - Less frequent because B $\neq$ 0
  - Bead pulling

Control issues

- Robot structure
- **Robot model**
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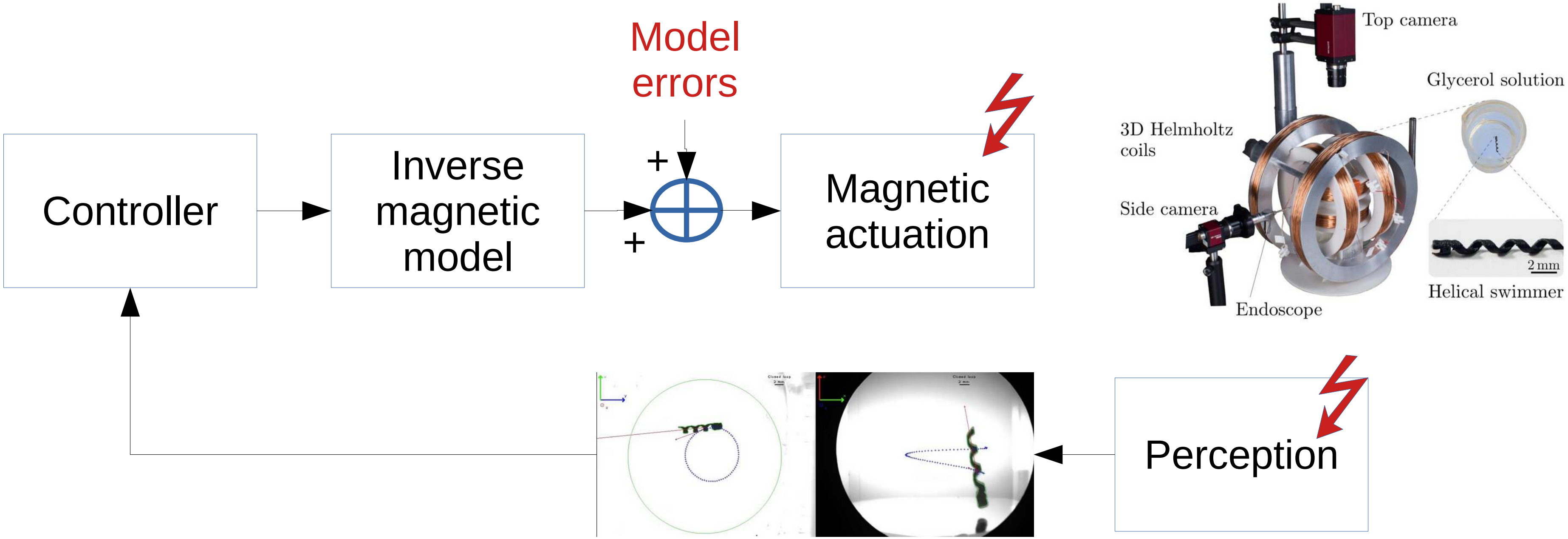
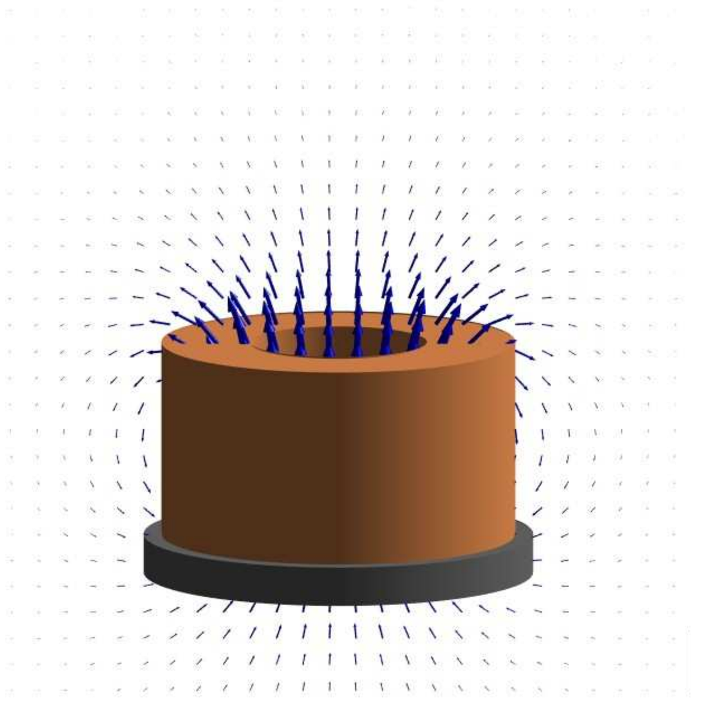
Magnetic field model

- **Requirements**
  - Fast → closed-loop control, real-time constraint
  - Accurate … but sensor-based control, so not ***that*** accurate



Magnetic field models

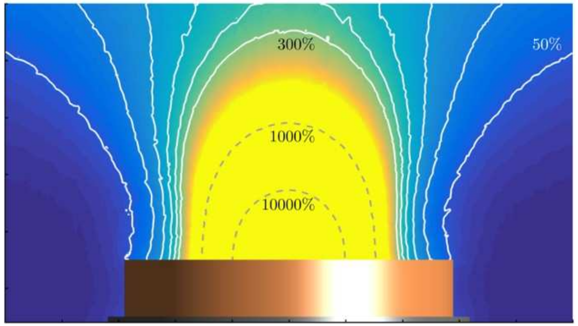
- **Specific configurations**
  - Helmholtz pair : B = cst at center (→ B ≈ cst everywhere)
  - Maxwell pair : B = 0 at center (→ F ≈ cst everywhere)
- **General case**
  - $\boldsymbol{B}(P) = \boldsymbol{b}(P).I$
  - Fast decay of B as P goes away
  - Non linear close to the source, smooth (linear) far away
  - Complex



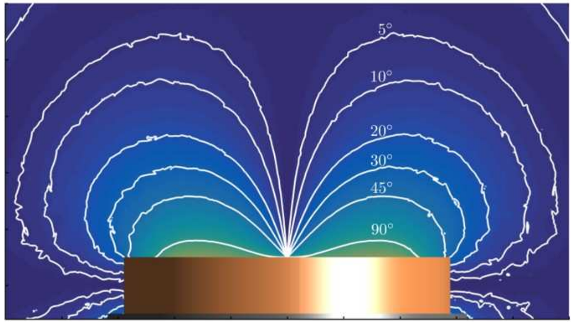
Champ magnétique produit par une bobine

Magnetic field models

- **Finite Element Model**
  - Accurate but sparse
  - Costly but pre-computed
  - Interpolation between samples but memory access cost
- **Mapping**
  - Same as above
  - Fits for any shape
- **Dipole model**
  - Circular loop
  - r >> a
  - Simple closed-form expression



Relative error on field norm wrt. FEM



Angular error wrt. FEM

Models based on magnetic potential vector

- **Circular loop**

$$\mathbf{b} = \nabla \wedge \mathbf{a} \quad \text{with} \quad \mathbf{a} = (A_r, A_\theta, A_\phi)^T$$ [Jackson99]

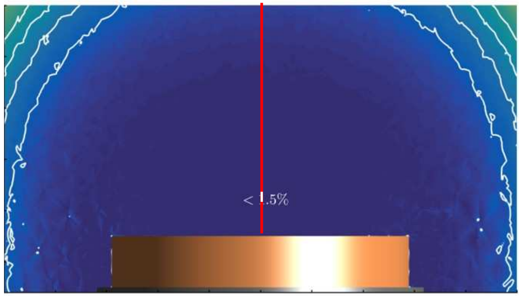
$$\begin{cases} A_r = 0 \\ A_\theta = 0 \\ A_\phi(r,\theta) = \frac{\mu_0 i}{\pi} \frac{a}{\sqrt{a^2 + 2ar\sin\theta + r^2}} \left[\frac{\left(2 - k^2\right) K(k) - 2E(k)}{k^2} \right] \\ k(r,\theta) = \sqrt{\frac{4ar\sin\theta}{a^2 + 2ar\sin\theta + r^2}} \end{cases}$$

Elliptic integral functions

$$K(k) = \int_0^{\frac{\pi}{2}} \frac{1}{\sqrt{\left(1 - k^2 \sin^2\alpha\right)}} d\alpha$$

$$E(k) = \int_0^{\frac{\pi}{2}} \sqrt{\left(1 - k^2 \sin^2\alpha\right)} d\alpha$$

- Almost as accurate as FEM
- Higher CPU cost : derivatives of K & E
- Not defined for r = 0 or θ = 0



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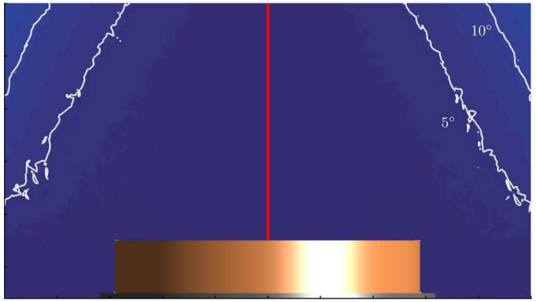


Angular error wrt. FEM

Control-oriented magnetic field model

- **Model based on the magnetic potential vector**
- **Use of an "old" formula**

$$\frac{\mathrm{d}K}{\mathrm{d}k}(k) = \frac{E(k)}{k\,(1-k^2)} - \frac{K(k)}{k}$$

$$\frac{\mathrm{d}E}{\mathrm{d}k}(k) = \frac{E(k)}{k} - \frac{K(k)}{k}$$

[Abramowitz72]

Pour tout $(r,\theta) \in D_{k^*}$ on a :

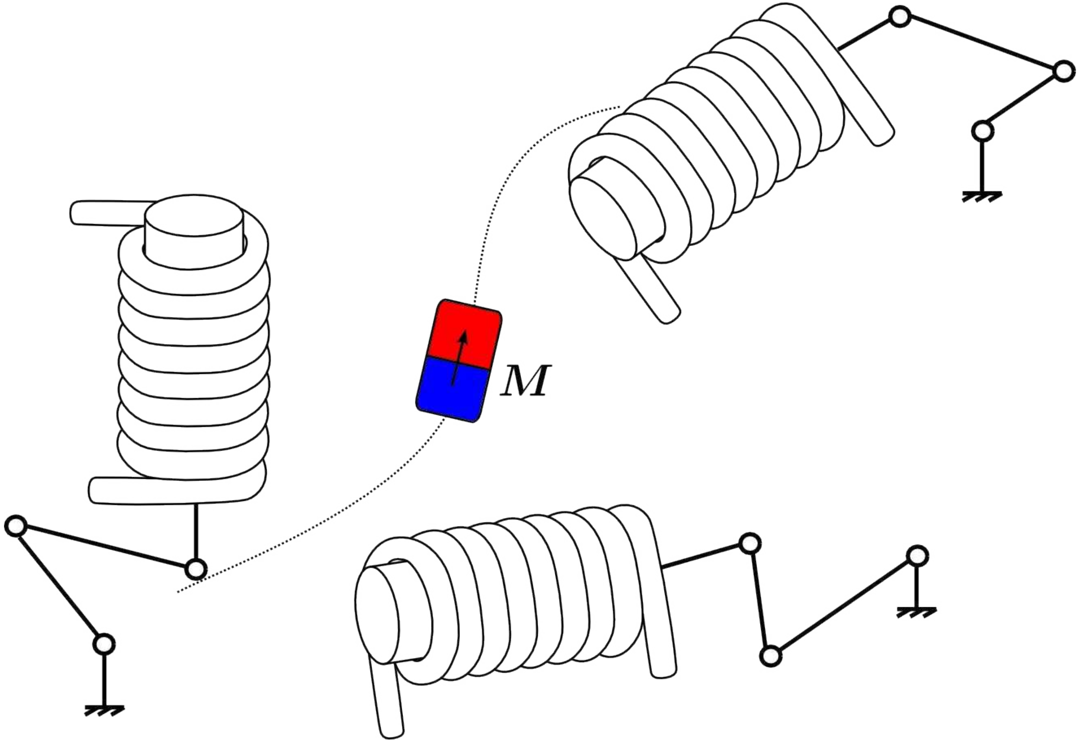
$$\begin{cases} b_r(r,\theta) = \dfrac{\mu_0 I}{\pi} \dfrac{a^2}{\sqrt{a^2+2ar\sin\theta+r^2}} \dfrac{E(k)\cos\theta}{a^2-2ar\sin\theta+r^2} \\ b_\theta(r,\theta) = \dfrac{\mu_0 I}{\pi} \dfrac{1}{\sqrt{a^2+2ar\sin\theta+r^2}} \left[\dfrac{E(k)\left(r^2+a^2\cos(2\theta)\right)}{(a^2-2ar\sin\theta+r^2)\,2\sin\theta} \right] \\ b_\phi = 0 \end{cases}$$

[Etiévant 19]

- **Smooth extension on the axis**

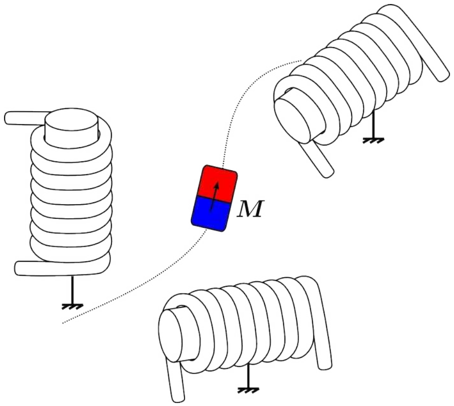
	Computation time (ms/point)	Standard deviation (ms)	Memory used (ko)
Mapping	162	1.583	$\geq$1400
Dipole	1.7	0.163	$\leq$6
Wong's formulation	1164.5	7.1	$\leq$7
Schill's formulation	241.4	2.5	$\leq$7
Extended formulation	3.6	0.147	$\leq$7

A generic model for multi-mobile source systems



Specific case

Static electromagnets



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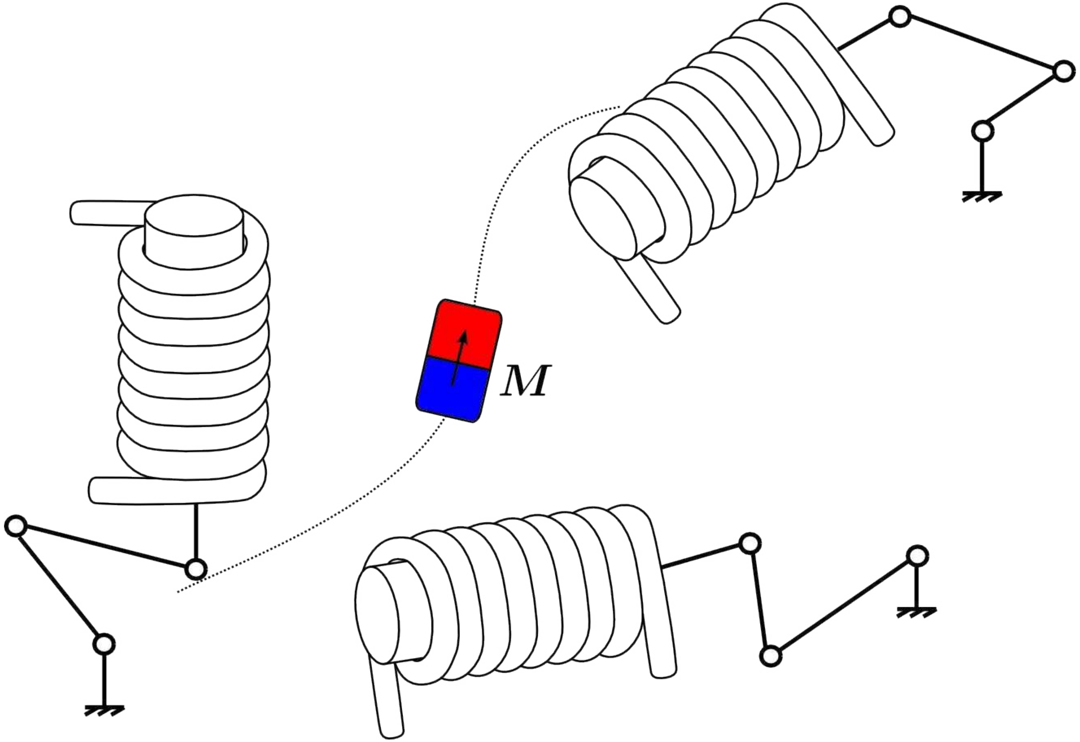
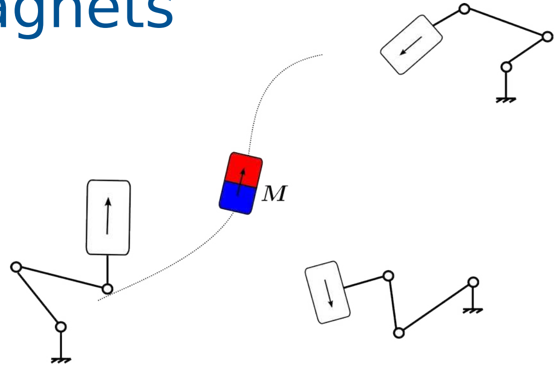


Specific case

Mobile permanent magnets



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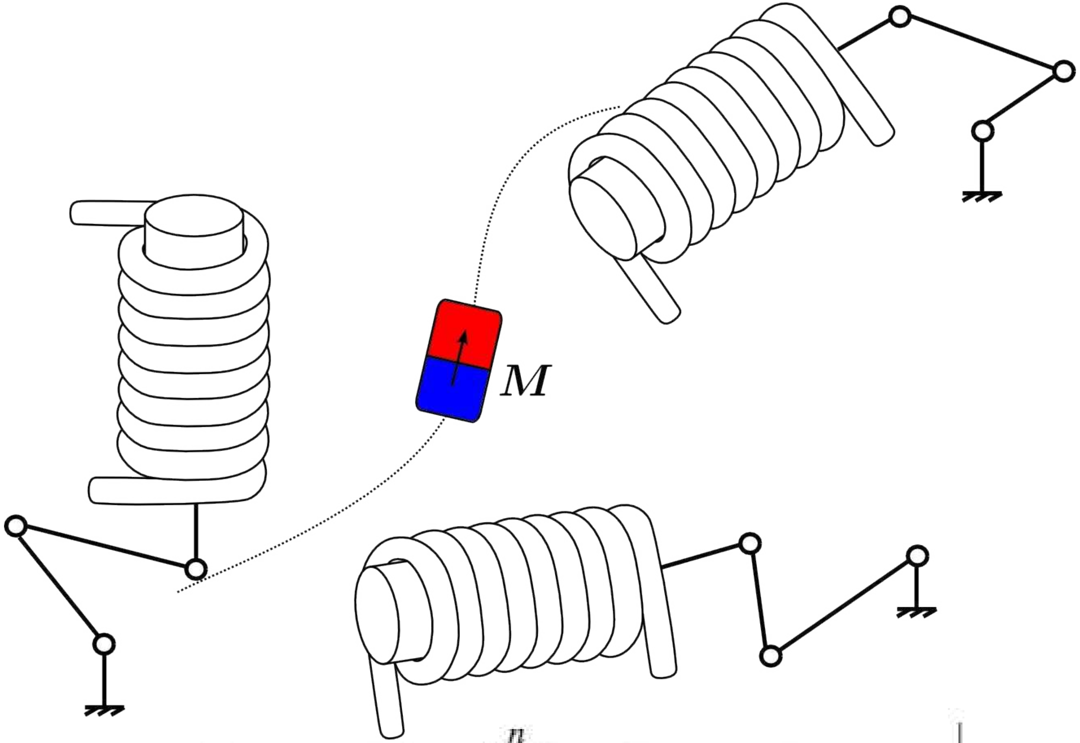

- **Superposition theorem**
- **Linear in the currents**
- **Non-linear in the source locations**
- **In robotic language: Forward Electromagnetic Model (FEmM)**

$$\begin{bmatrix} \boldsymbol{f} \\ \boldsymbol{b} \end{bmatrix} = FEmM\left(\{{}^0T_i\}_{i=1..n}, \boldsymbol{I}\right)$$

$$\boldsymbol{B}\left(\{{}^j\mathbf{T}_0\}_j, {}^0\tilde{\mathbf{p}}\right) = \sum_{j=1}^{n} {}^0\mathbf{R}_j {}^j\mathbf{b}_j({}^j\mathbf{T}_0\, {}^0\tilde{\mathbf{p}}) i_j = \mathbf{A}\left(\{{}^j\mathbf{T}_0\}_j, {}^0\tilde{\mathbf{p}}\right)\mathbf{i}$$

$$\mathbf{f}\left(\{{}^j\mathbf{T}_0\}_j, {}^0\tilde{\mathbf{p}}, \mathbf{m}\right) = \sum_{j=1}^{n} {}^0\mathbf{R}_j {}^j\mathbf{f}_j({}^j\mathbf{T}_0\, {}^0\tilde{\mathbf{p}}, \mathbf{m}) i_j = \mathbf{F}\left(\{{}^j\mathbf{T}_0\}_j, {}^0\tilde{\mathbf{p}}, \mathbf{m}\right)\mathbf{i}$$

[Véron 14]

Control issues

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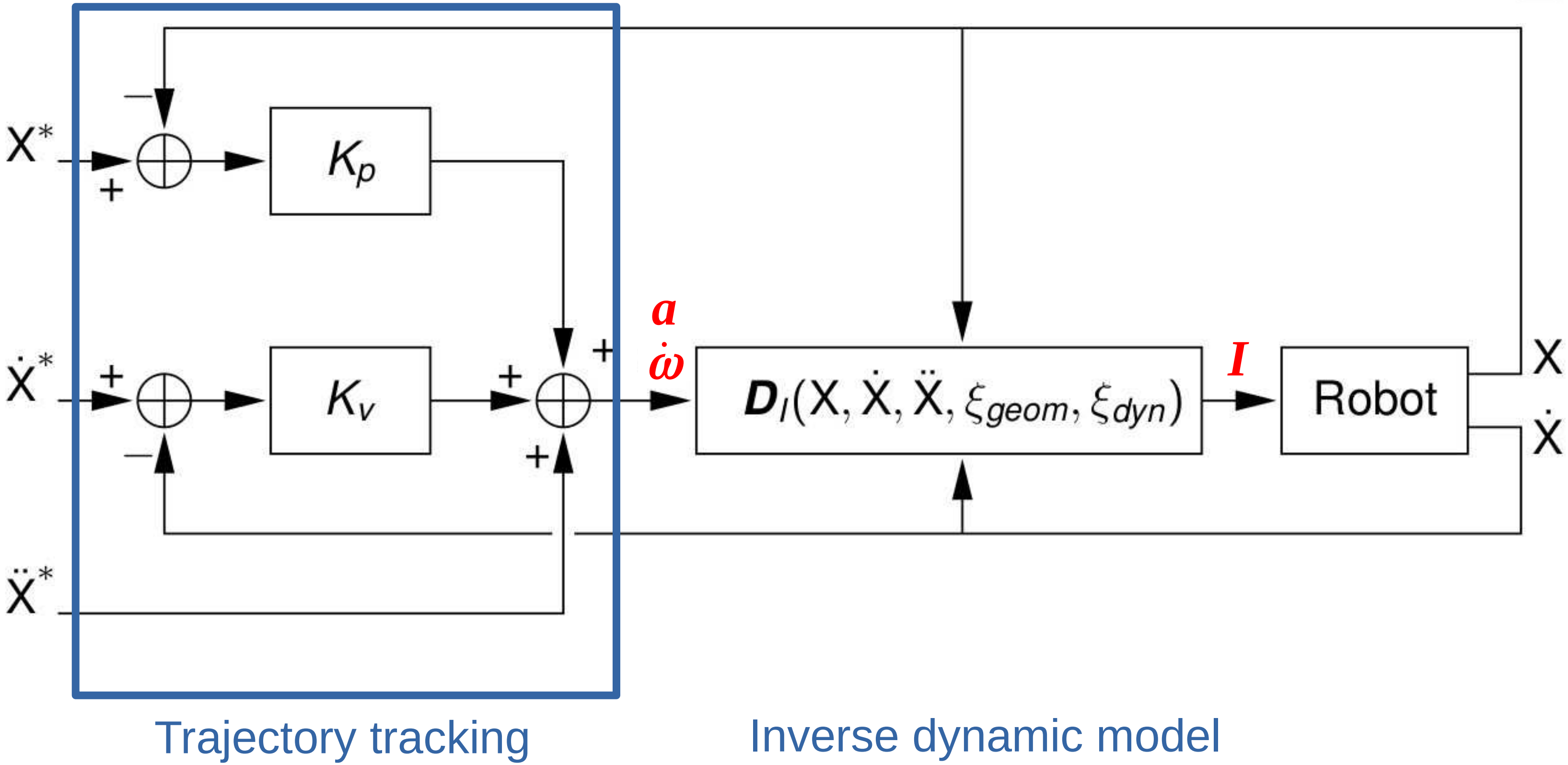
- **Control scheme**

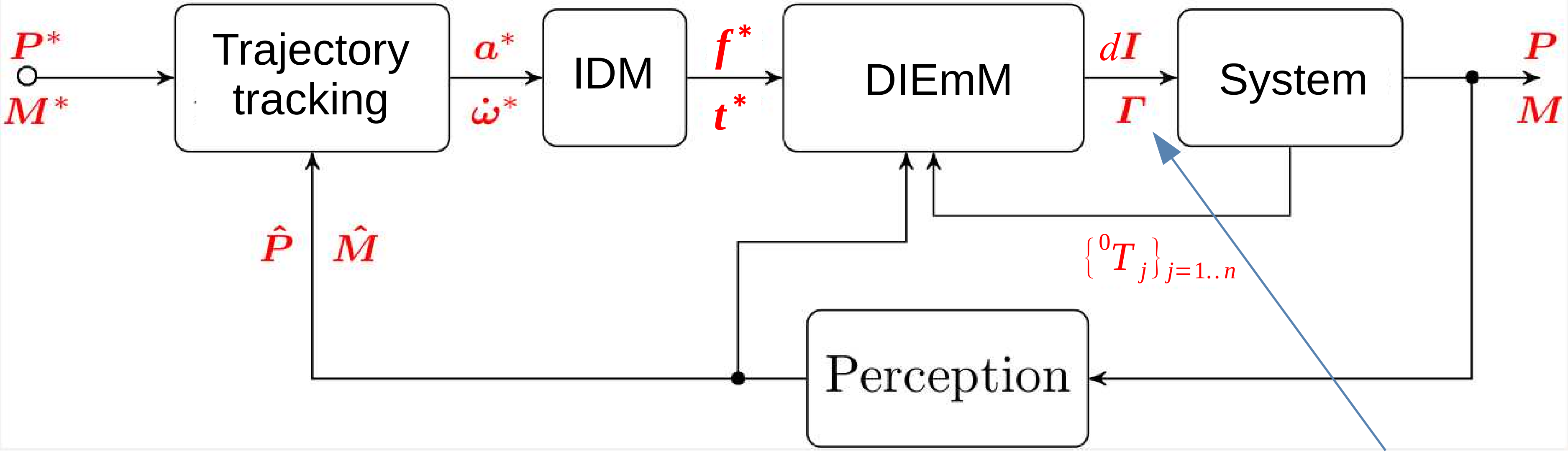
Dynamic control

- **Computed-torque control**



Computed Twist-and-Current Control

DIEmM =
Differential Inverse Electromagnetic Model



$$\Gamma = \begin{bmatrix} \gamma_1 \\ \vdots \\ \gamma_n \end{bmatrix} \qquad \gamma_j = \begin{bmatrix} \vec{v}_j \\ \vec{\Omega}_j \end{bmatrix}$$

Non-linear control by linearisation

- **Forward Electromagnetic Model (FEmM)**

$$\begin{bmatrix} \boldsymbol{f} \\ \boldsymbol{t} \end{bmatrix} = \boldsymbol{F}_{EmM}\left(\left\{{}^0T_j\right\}_{j=1..n}, \boldsymbol{I}\right)$$

non linear

- **Inverse Electromagnetic Model (IEmM)**

$$\left\langle \left\{{}^0T_j\right\}_{j=1..n}, \boldsymbol{I} \right\rangle = \boldsymbol{FEmM}^{-1}(\boldsymbol{f}, \boldsymbol{t})$$

solution to a non linear equation !
→ Linearisation

- **Differential Forward Electromagnetic Model (DFEmM) / DIEmM**

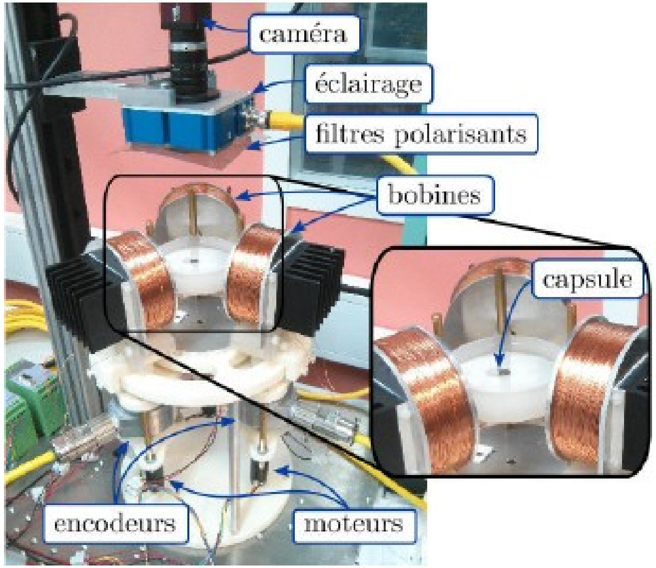
$$\begin{bmatrix} d\boldsymbol{f} \\ d\boldsymbol{t} \end{bmatrix} = \boldsymbol{J}_{Em}\left(\left\{{}^0T_j\right\}_{j=1..n}, \boldsymbol{I}\right) * \begin{bmatrix} d\boldsymbol{I} \\ \boldsymbol{\Gamma} \end{bmatrix}$$

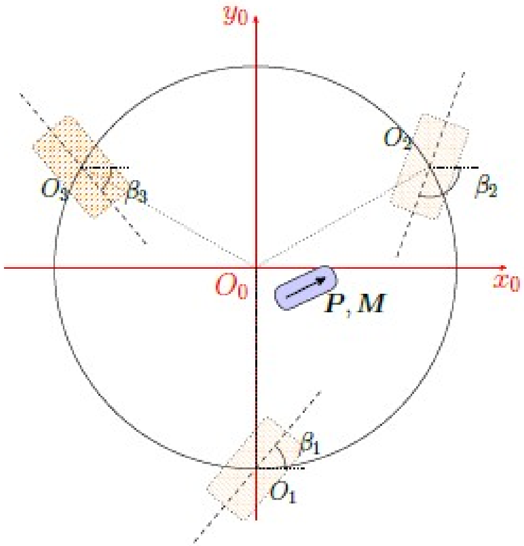
$$\begin{bmatrix} d\boldsymbol{I} \\ \boldsymbol{\Gamma} \end{bmatrix} = \boldsymbol{J}_{Em}^{inv}(\boldsymbol{f}, \boldsymbol{t}) * \begin{bmatrix} d\boldsymbol{f} \\ d\boldsymbol{t} \end{bmatrix}$$

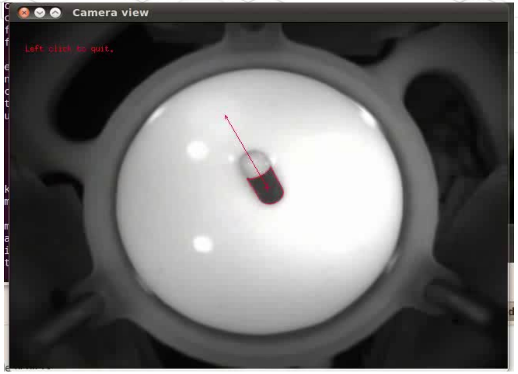
- **Proportional linearised controller**

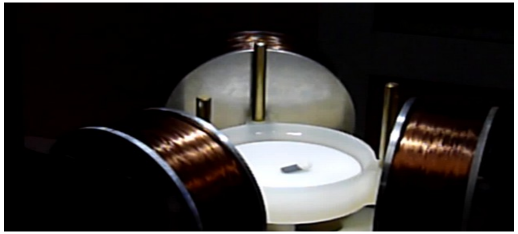
$$\begin{bmatrix} d\boldsymbol{I} \\ \boldsymbol{\Gamma} \end{bmatrix} = k_p * \boldsymbol{J}_{Em}^{inv}\left(\boldsymbol{FEmM}\left(\left\{{}^0T_j\right\}_{j=1..n,k-1}, \boldsymbol{I}_{k-1}\right)\right) * \begin{bmatrix} \boldsymbol{f}^* - \boldsymbol{f}_{k-1} \\ \boldsymbol{t}^* - \boldsymbol{t}_{k-1} \end{bmatrix}$$

Experimental validation









Control issues

- Robot structure
- Robot model
- **Kinematic analysis**
- Desired motion
- Control scheme

« Kinematic » analysis

- **Singularities**

$$\begin{bmatrix} d\boldsymbol{f} \\ d\boldsymbol{t} \end{bmatrix} = \boldsymbol{J}_{Em}(\cdots) * \begin{bmatrix} d\boldsymbol{I} \\ \boldsymbol{\Gamma} \end{bmatrix} \quad , \quad \begin{bmatrix} d\boldsymbol{I} \\ \boldsymbol{\Gamma} \end{bmatrix} = \boldsymbol{J}_{Em}^{inv}(\cdots) * \begin{bmatrix} d\boldsymbol{f} \\ d\boldsymbol{t} \end{bmatrix}$$

$$rank(\boldsymbol{J}_{Em}) dim(\boldsymbol{J}_{Em}) = 6 \times 7n \Rightarrow rank(\boldsymbol{J}_{Em}) \leq 5$$

if (rank < 5) J_{Em} is singular => serial singularity : can not update the full wrench

- **Null space**

$$dim(\boldsymbol{J}_{Em}) = 6 \times 7n \Rightarrow rank(\boldsymbol{J}_{Em}) < 5 \Rightarrow dim\,ker(\boldsymbol{J}_{Em}) \geq 7n - 5$$

Many infinitely many ways to change the configuration of the magnetic manipulator for the control of 1 magnetic object/tool

→ Manipulate several objects : max 5 dof/object, thus up to 7n/5 objects !

→ Use this redundancy to optimise additional cost functions

e.g. manipulability, collisions, energetic cost, ...

« Kinematic » analysis

- **Manipulability**

$$\begin{bmatrix} d\boldsymbol{f} \\ d\boldsymbol{t} \end{bmatrix} = \boldsymbol{J}_{Em}(\cdots) * \begin{bmatrix} d\boldsymbol{I} \\ \boldsymbol{\Gamma} \end{bmatrix}$$

How “good” is J_{Em} at updating the wrench ?

Numerical index : condition number $\kappa = \frac{\sigma_1}{\sigma_6}$

First manipulability index : $\mu = \frac{1}{\kappa}$

Many other manipulability indices

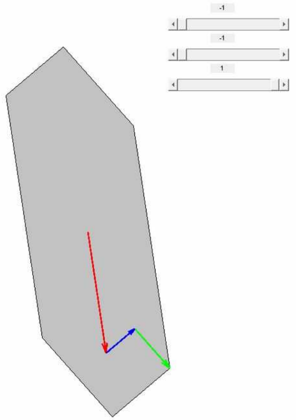
- **From PKM wrench feasible workspace…**

Tension

$$\text{WFW} = \left\{ \mathbf{F} \in \mathbb{R}^6 \mid \mathbf{F} = \mathbf{J}^{-T} \cdot \tau,\ 0 \leq \tau \leq \tau_{max} \right\}$$

… to the achievable field workspace

$$E_B\left(\{{}^0T_j\}_{j=1..n}, P\right) = \left\{ \boldsymbol{B}\left(\{{}^0T_j\}_{j=1..n}, P\right),\ \ \boldsymbol{B}(\cdots) = \sum_{j=1}^{n} \boldsymbol{b}_j(\cdots) I_j, |I_j| \leq I_{max} \right\}$$



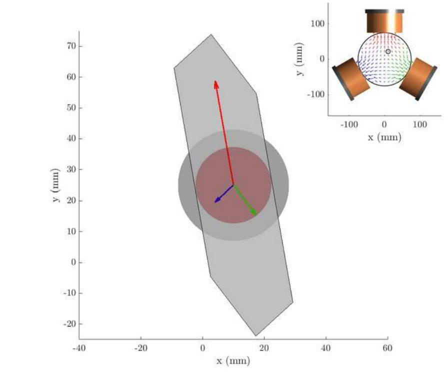
« Kinematic » analysis

- **From the achievable field workspace**

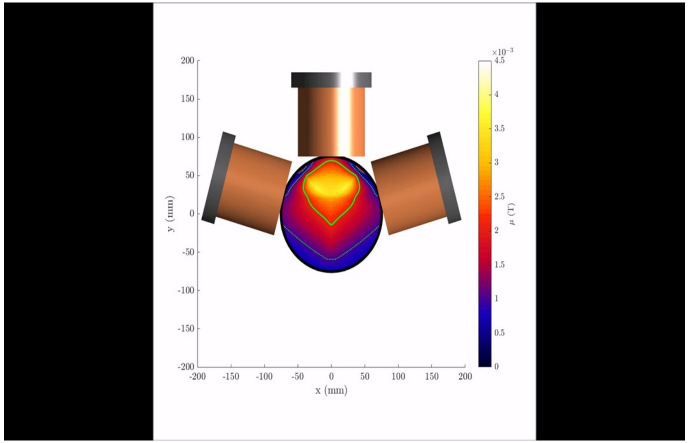
$$E_B(\{{}^0T_j\}_{j=1..n}, P) = \left\{ \mathbf{B}\left(\{{}^0T_j\}_{j=1..n}, P\right), \;\; \mathbf{B}(\cdots) = \sum_{j=1}^{n} \mathbf{b}_j(\cdots) I_j, |I_j| \le I_{max} \right\}$$

… to a magnetic manipulability index

$$\mu(P) = \max_{\vec{e}} \left\{ \mathbf{B}\left(\{{}^0T_j\}_{j=1..n}, P\right) \cdot \vec{e}, \;\; \mathbf{B}(\cdots) \in E_B, |\vec{e}| = 1 \right\}$$



- **Dexterity map**

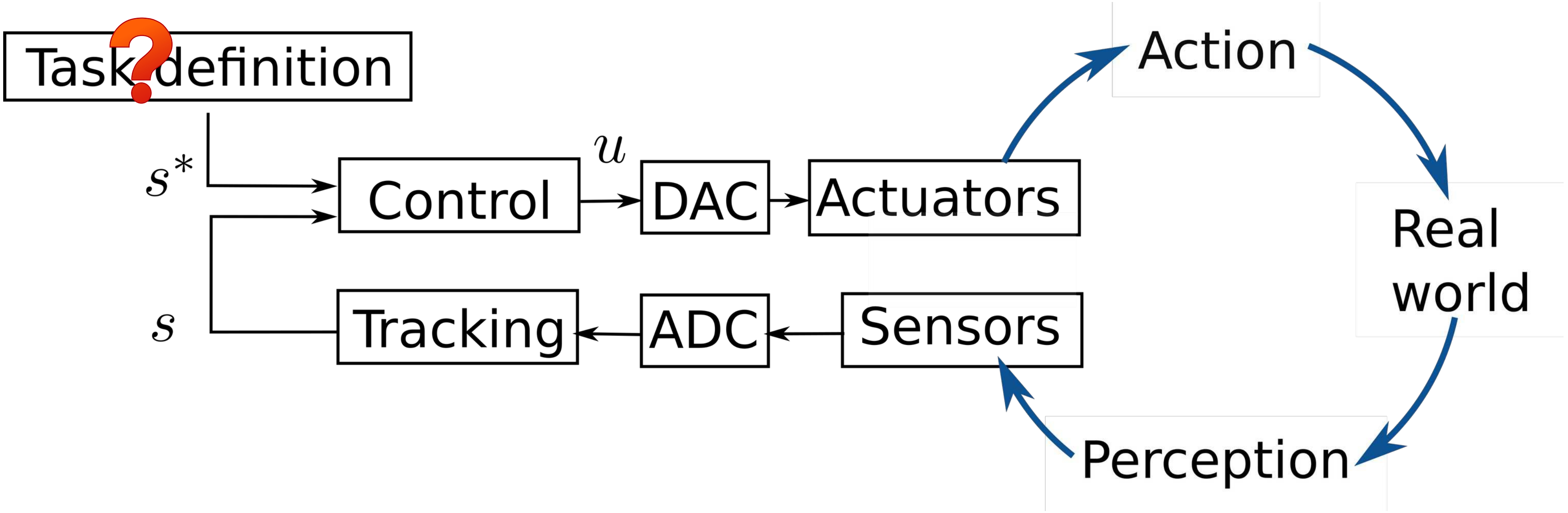


Control issues

- Robot structure
- Robot model
- Kinematic analysis
- **Desired motion**
- Control scheme

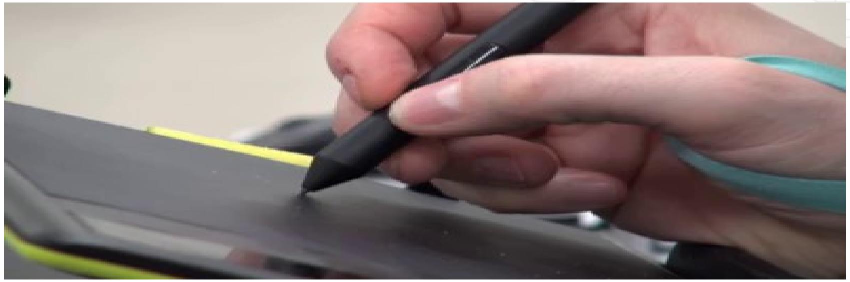
Keep control at any time !

What is a magnetic manipulation system?



User needs and robotics practice

- **User ≠ robotics expert**
- **User needs and Task design**
  - Ergonomic
  - Simple
  - Accurate



- **Trajectory definition**
  - Discrete set of waypoints

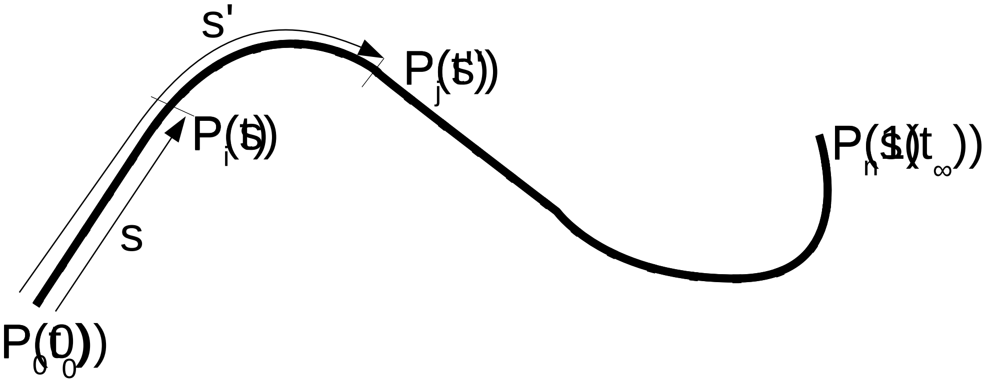
$$\boldsymbol{S}=\{\boldsymbol{P}_i, i=1..n\}$$

  - Path = continuous curve

$$\boldsymbol{C}=\{\boldsymbol{P}(s), s\in[0,1]\}$$

  - Trajectory = timed waypoints

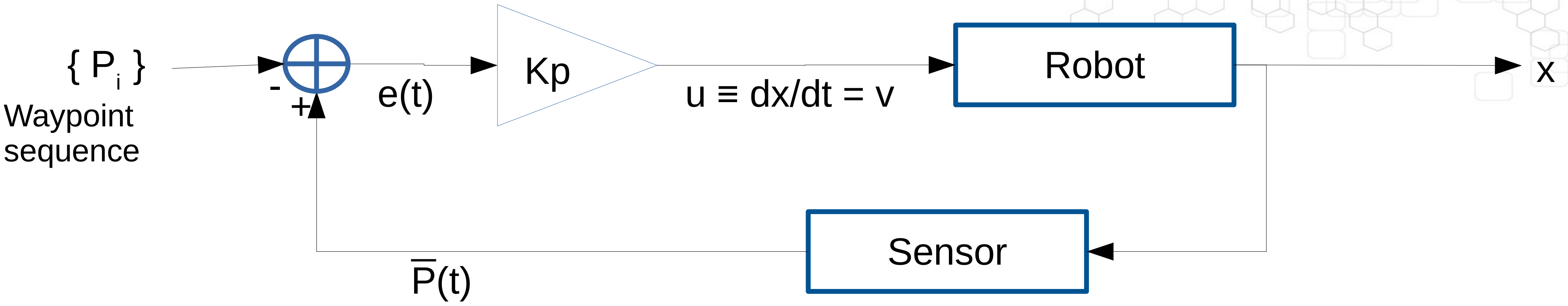
$$\boldsymbol{T}=\{\boldsymbol{P}(t), t\in[t_0, t_{inf}]\}$$



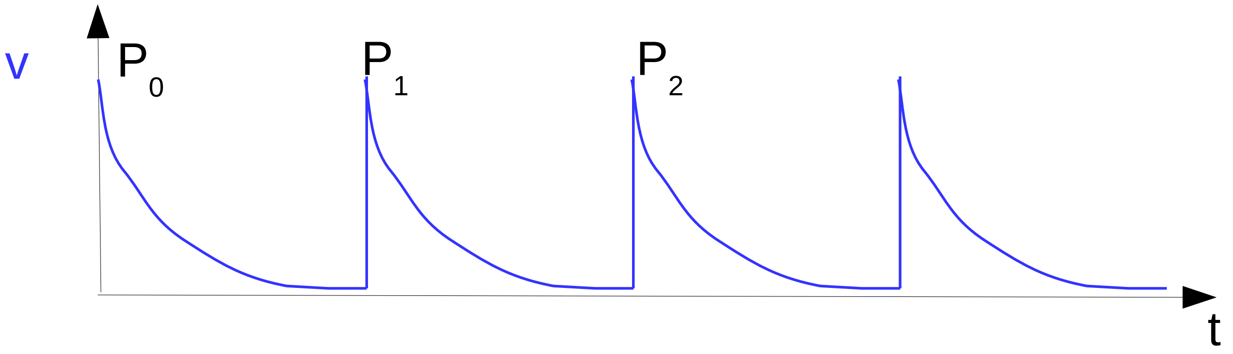
Control issues

- Robot structure
- Robot model
- Kinematic analysis
- Desired motion
- **Control scheme**

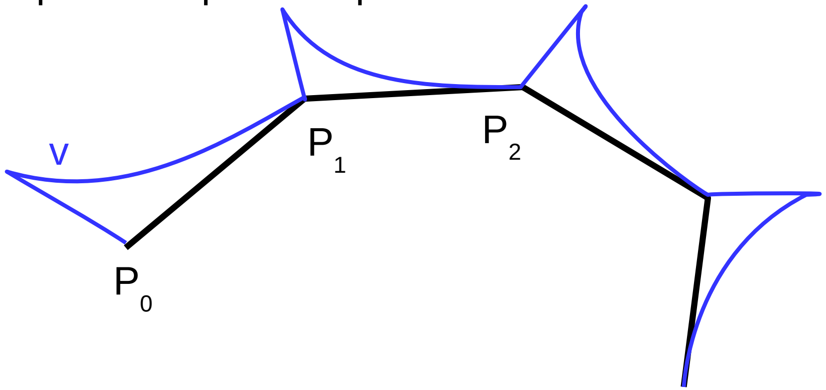
Standard controller



Time response



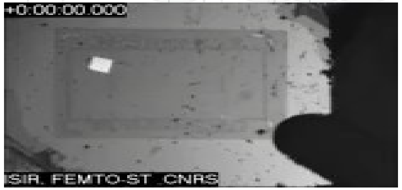
Spatio-temporal response



Standard controller at small scale

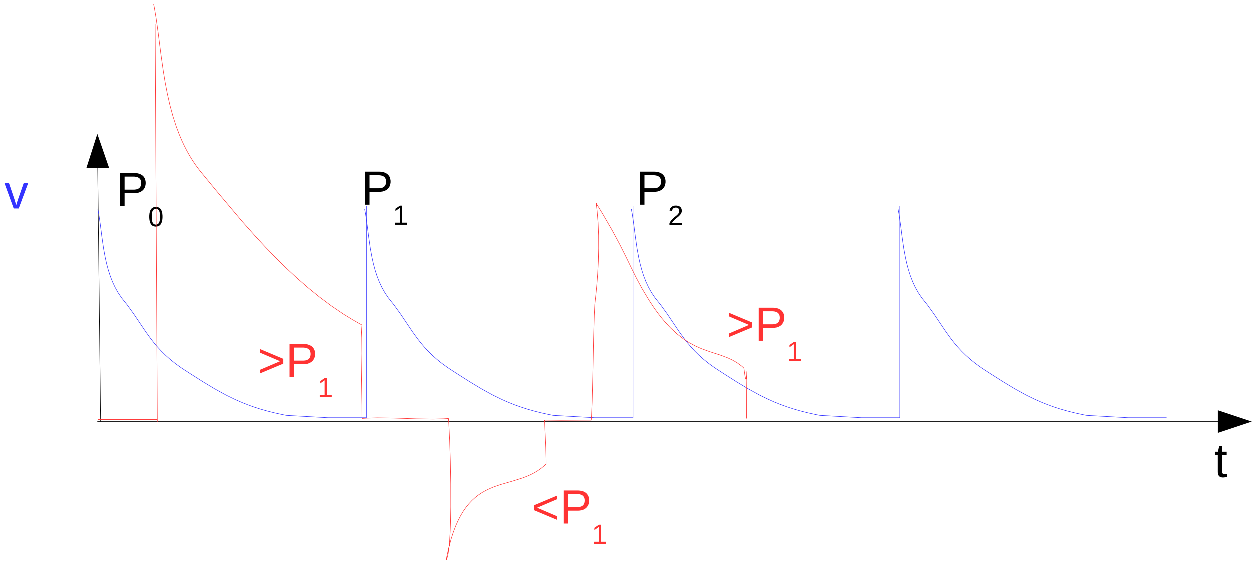
MagPier experience :

Small robot in the air over a surface = dry friction

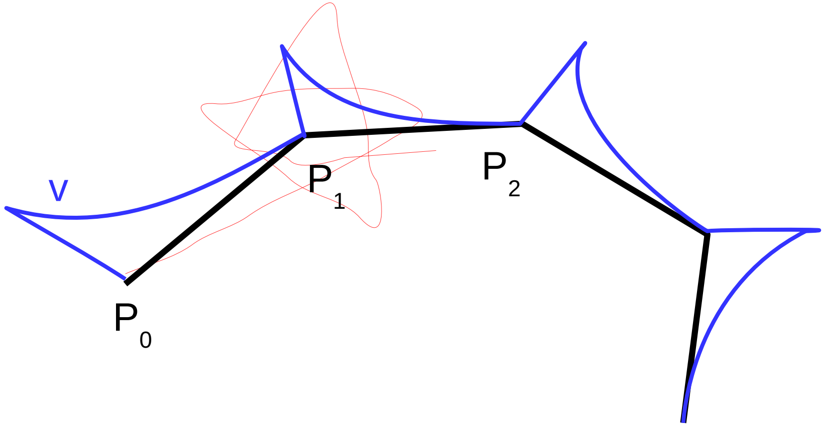


ICRA/NIST Challenge 2011 : MagPier @ ISIR/FEMTO-ST

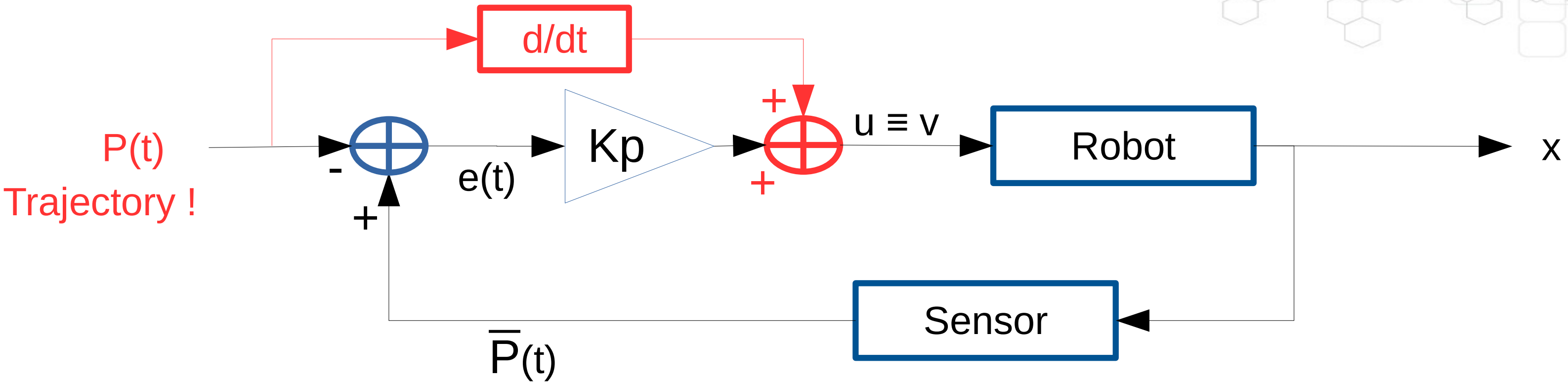
Time response



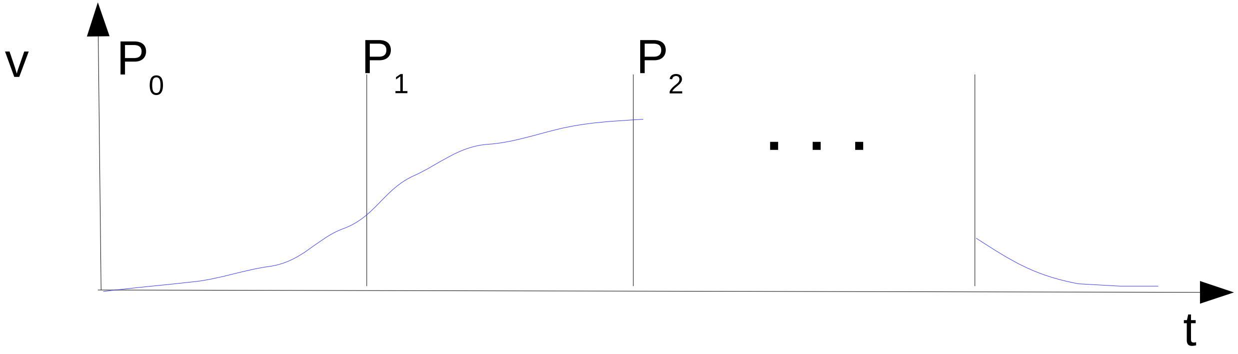
Spatio-temporal response



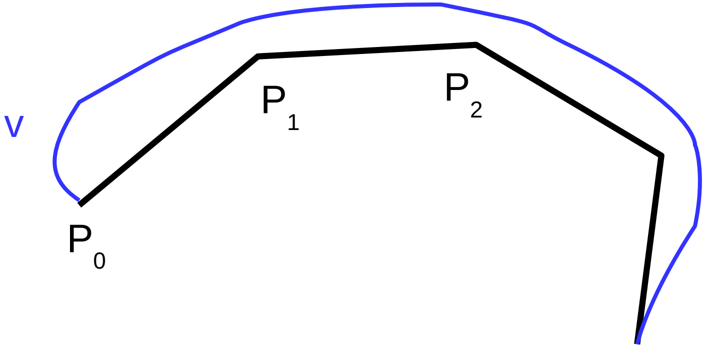
Proportional + feedforward controller



Time response



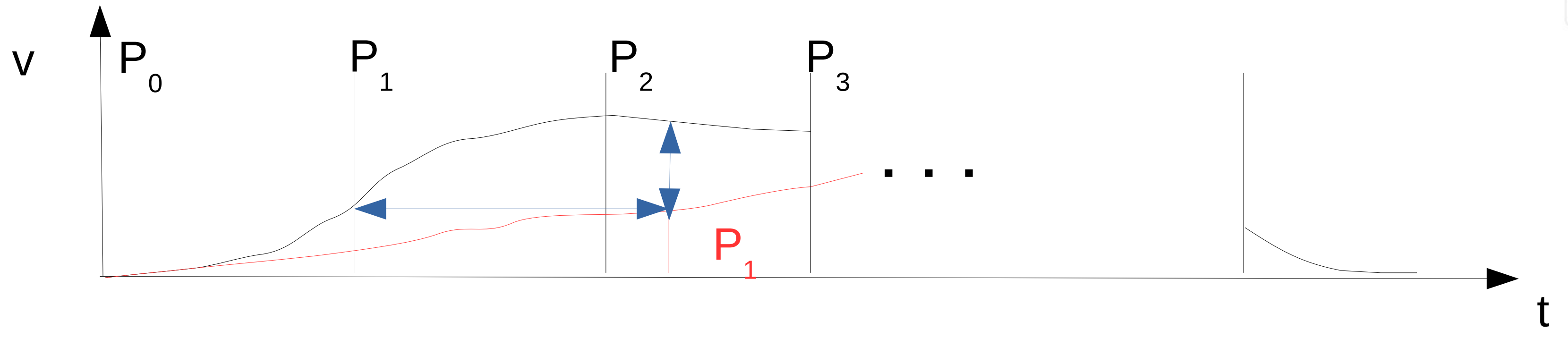
Spatio-temporal response

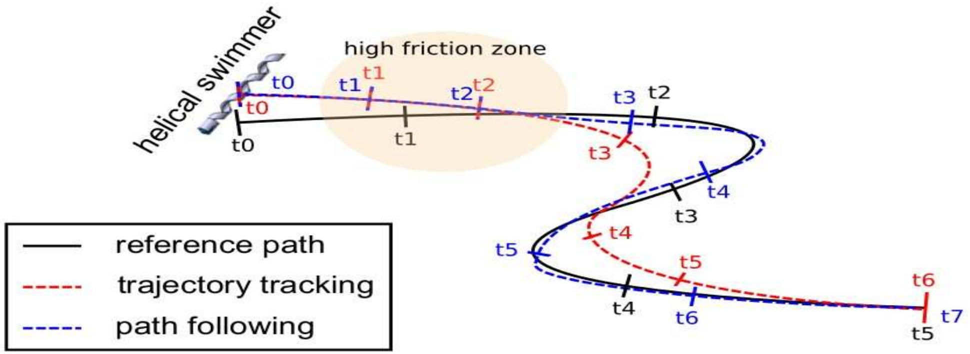


Dry friction reduced but trajectory planning is more complex than defining waypoints

Golden Eye reloaded

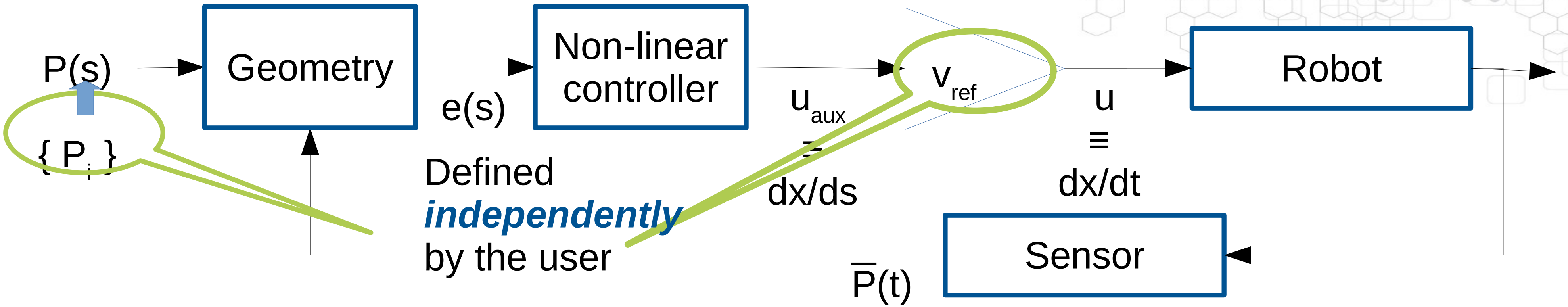
Viscous/dry friction → time delay → P_2 was missed → now aiming at P_3



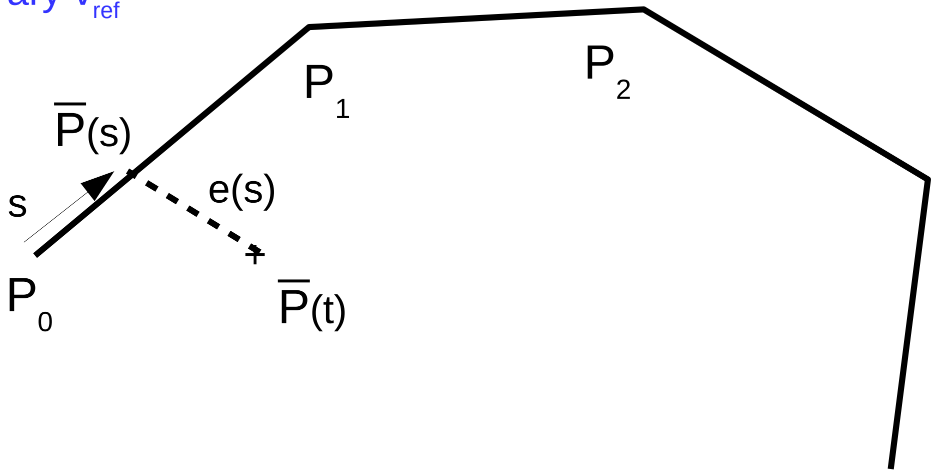


Time is
the problem !

A controller respecting the geometry



arbitrary v_{ref}



Time-independent error

Arbitrary velocity

⇒ **Time and space are decoupled**

⇒ **User need satisfied**

⇒ but NL controller to be defined

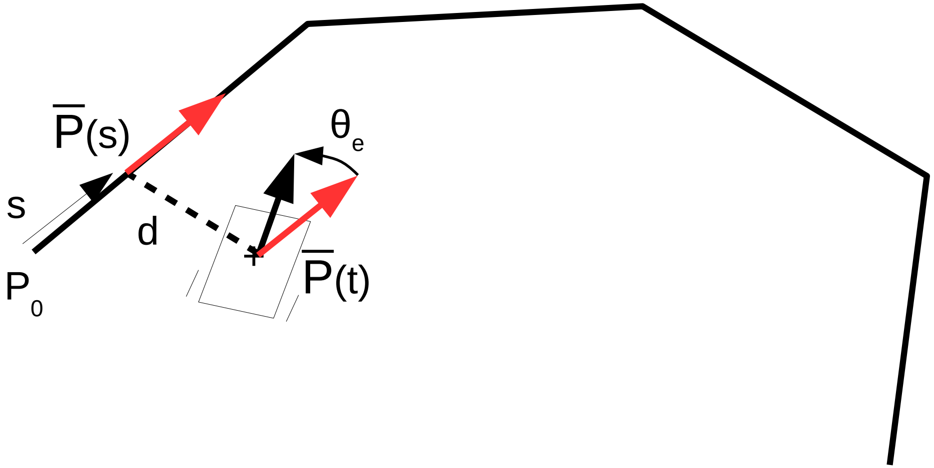
Non holonomic vehicle control

Vehicle state : s, d, θ_e

Vehicle control inputs : $u_1 = ||v||$ $u_2 = \omega$

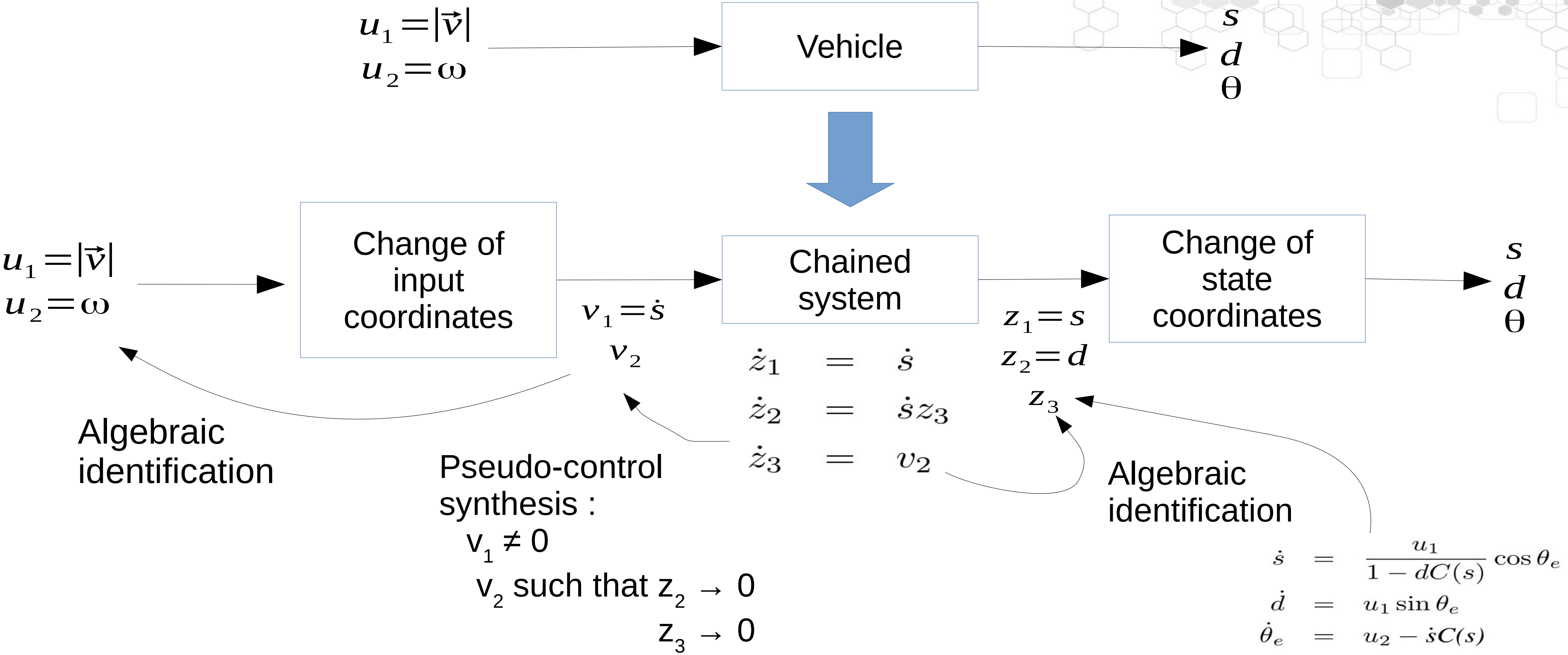
Vehicle kinematics :

$$\begin{aligned} \dot{s} &= \frac{u_1}{1 - dC(s)} \cos\theta_e \\ \dot{d} &= u_1 \sin\theta_e \\ \dot{\theta}_e &= u_2 - \dot{s}C(s) \end{aligned}$$



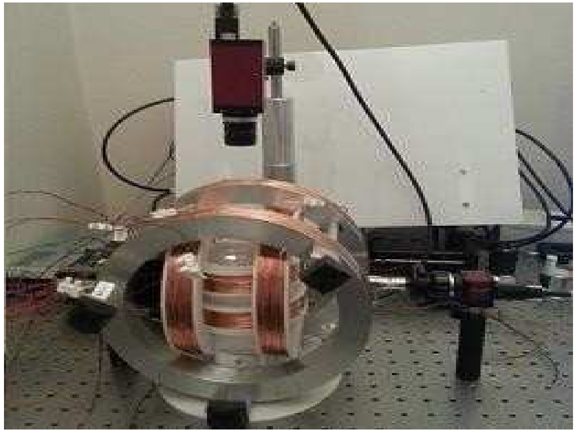
Non-linear
Time-dependent
Non-holonomic

Exact linearisation and cascade control

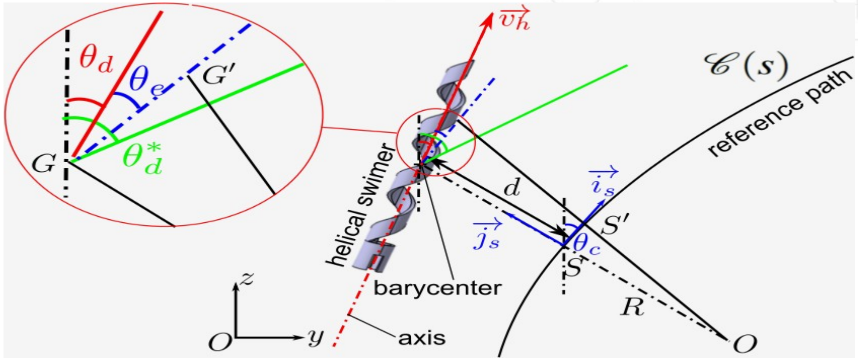


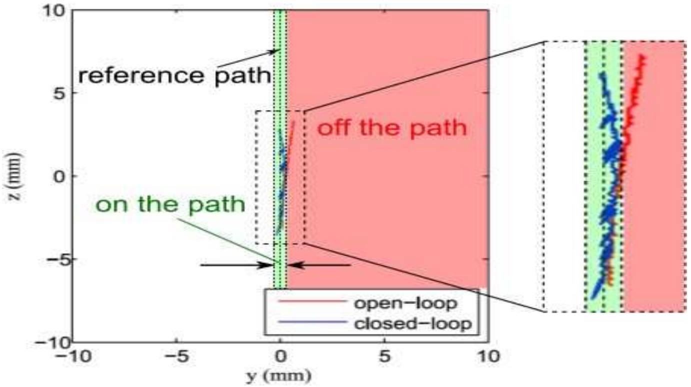
This is how you drive : wheel and throttle decoupled in normal conditions (e.g. cruise control)

Scaled-up helical swimmer in 2D



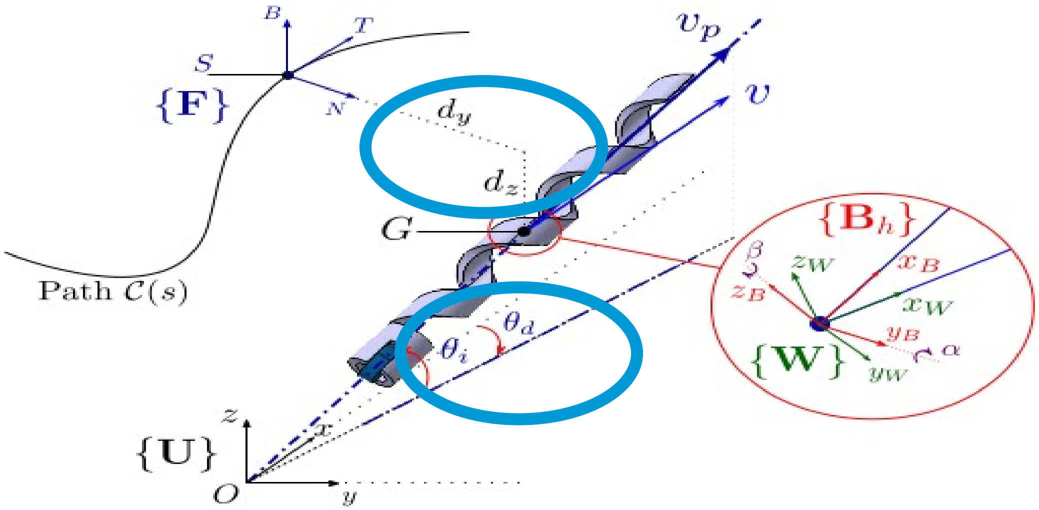
Helical swimming is non holonomic

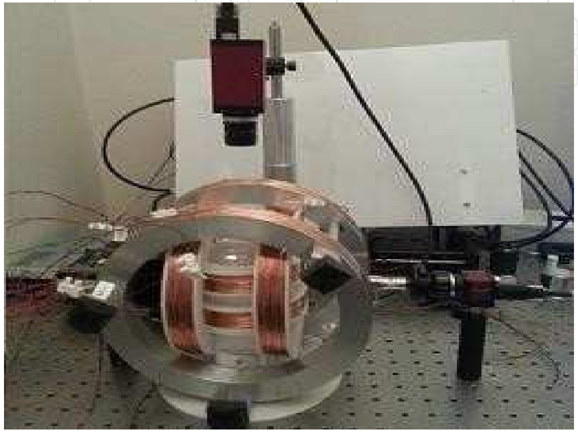




open-loop control of the height + closed-loop control in the horizontal plane [Xu 14]

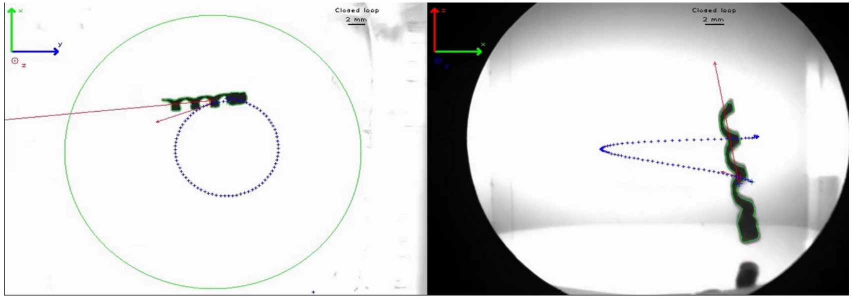
Extension to magnetic swimming in 3D



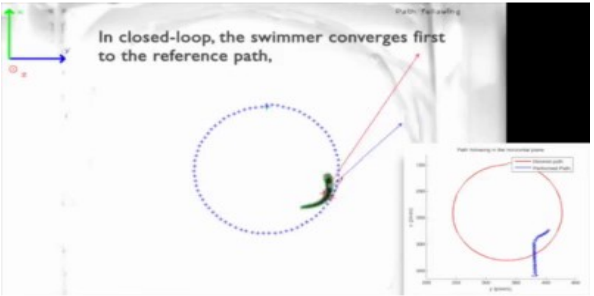


From a 3-state (s,d,θ) 2-input (|v|,ω) chained system
to a 5-state (s,dx,dy,θ_x, θ_y) 3-input (|v|,ω_x,ω_y) chained system

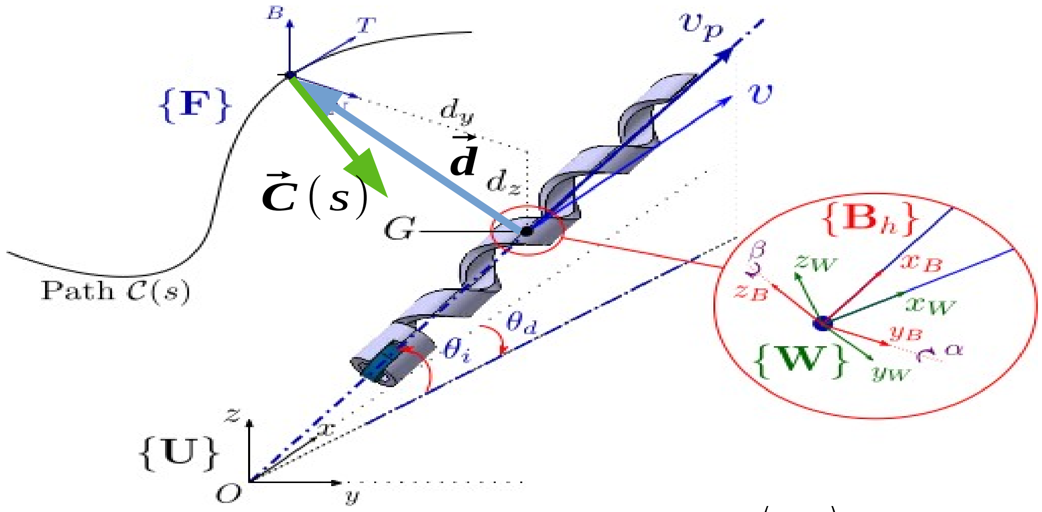
+ independence from propulsion mode



[Oulmas 18]



Towards a simpler formalism



State : Algebraic analysis (incl. curvature) $\begin{pmatrix} s \\ \vec{d} \\ \vec{v}_p \end{pmatrix}$

$$\dot{\vec{d}} = \left(I - \frac{\vec{x}_s \vec{x}_s^T}{1 - \vec{d}^T \vec{C}(s) \times \vec{T}} \right) \vec{u}_1$$

Input : Geometric controller $\vec{u}_1 = u_1 \vec{v}_p$

$$\vec{u}_1 = \alpha \vec{T} + \beta \vec{d}$$

$$|\vec{u}_1| = arbitrary \Rightarrow \alpha = \sqrt{|\vec{u}_1|^2 - \beta^2 |\vec{d}|^2}$$

→ Lyapunov stability ?

Take home messages

- **A microswimmer is not a robot**
- **A new class of magnetic manipulation systems**

  multi-mobile electromagnet systems
- **Several modes of actuation**

  Field only, Force/Field, (Force only)
- **Two control strategy**

  trajectory tracking, path following
- **A control-oriented magnetic model**

  fast and accurate enough
- **Typical robotic issues**

  Manipulability, dexterity, singularities

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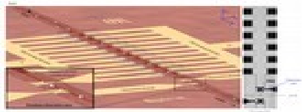



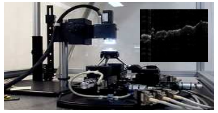
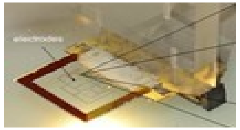

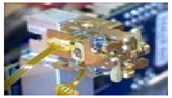
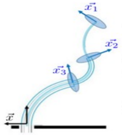
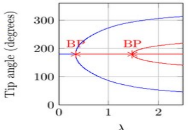

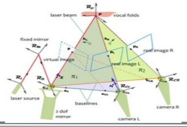

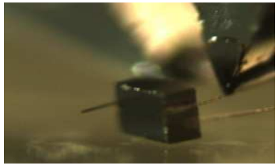
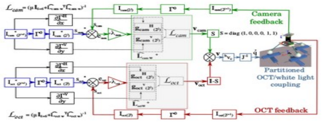


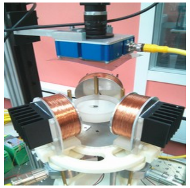

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