PERFORMANCE METRICS FOR A ROBOTIC ACTUATION SYSTEM USING STATIC AND MOBILE ELECTROMAGNETS

Chen Ruipeng, David Folio, Antoine Ferreira

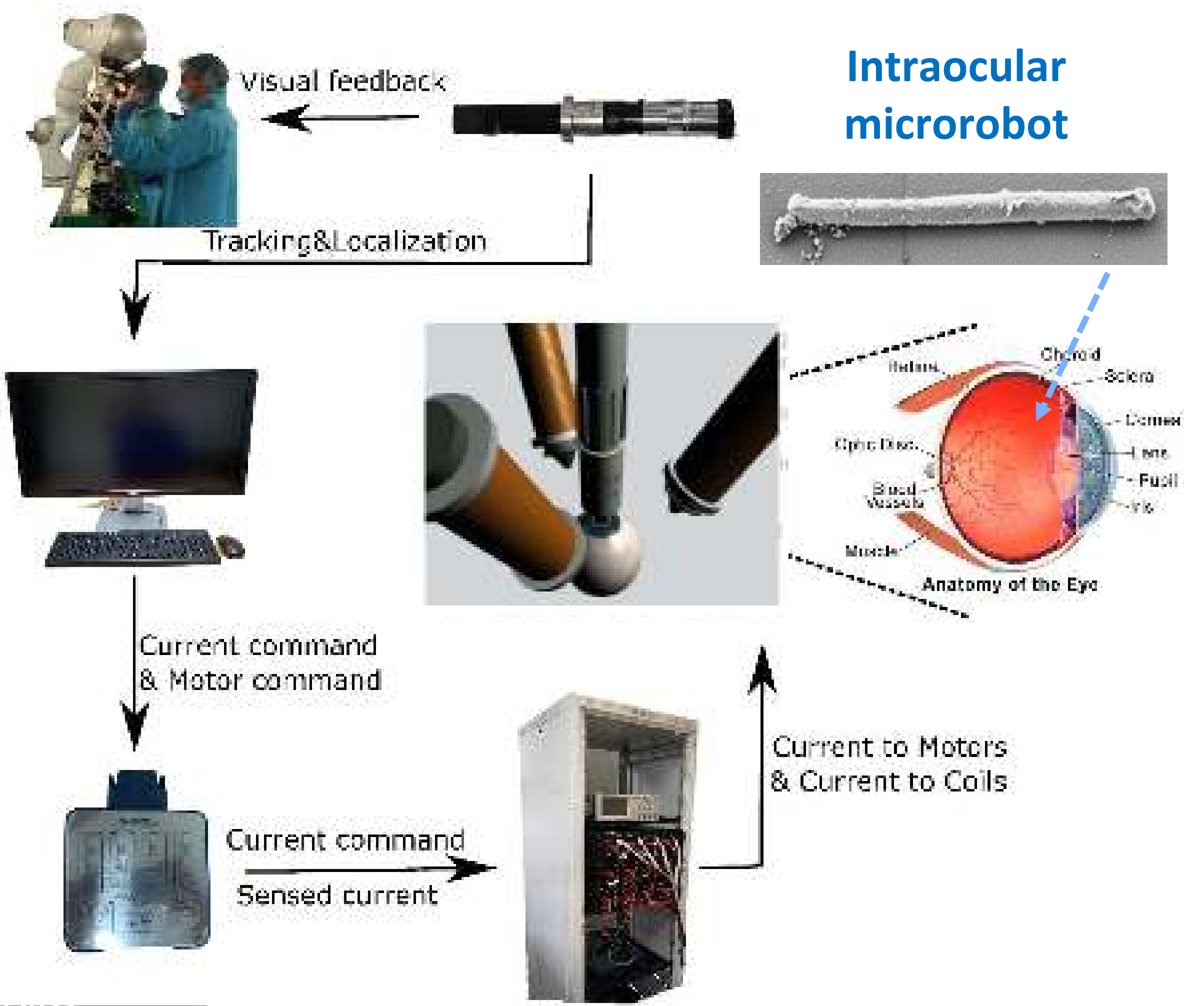
Laboratoire PRISME

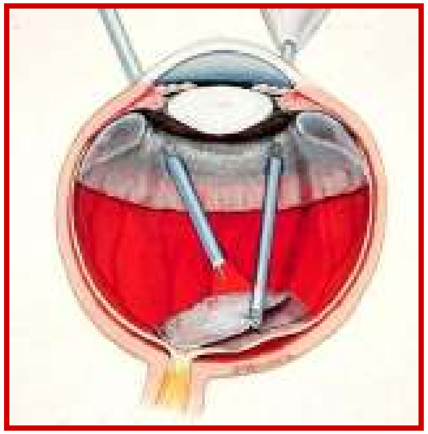
Institut National des Sciences Appliquées de Centre Val de Loire

Bourges 18000, France

INTRODUCTION

- **Objective:** **Proposed retinal procedures are at the limits of human performance and perception.**

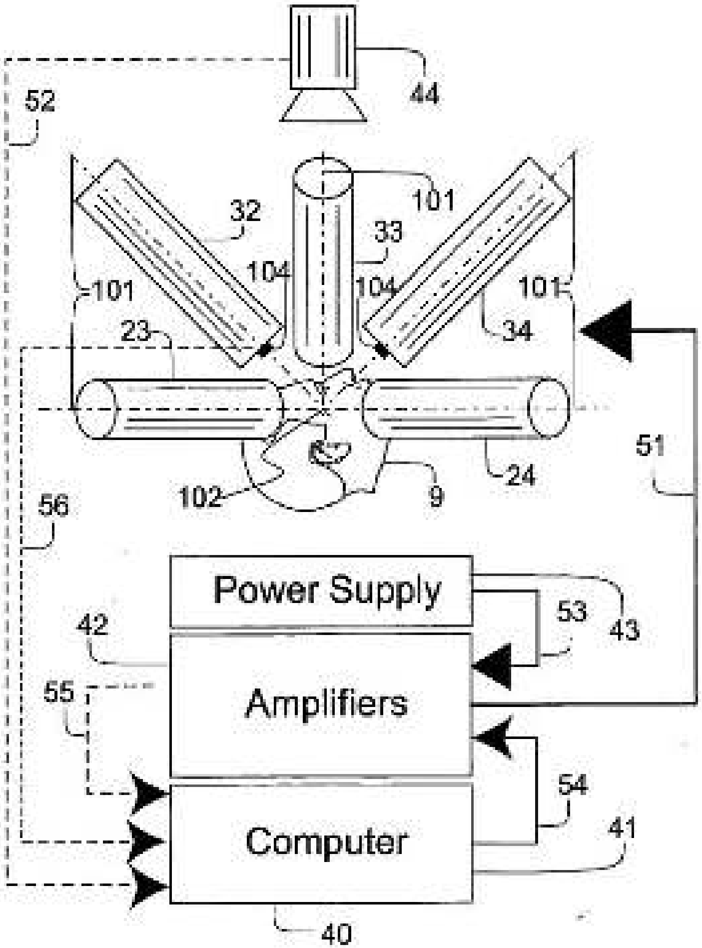


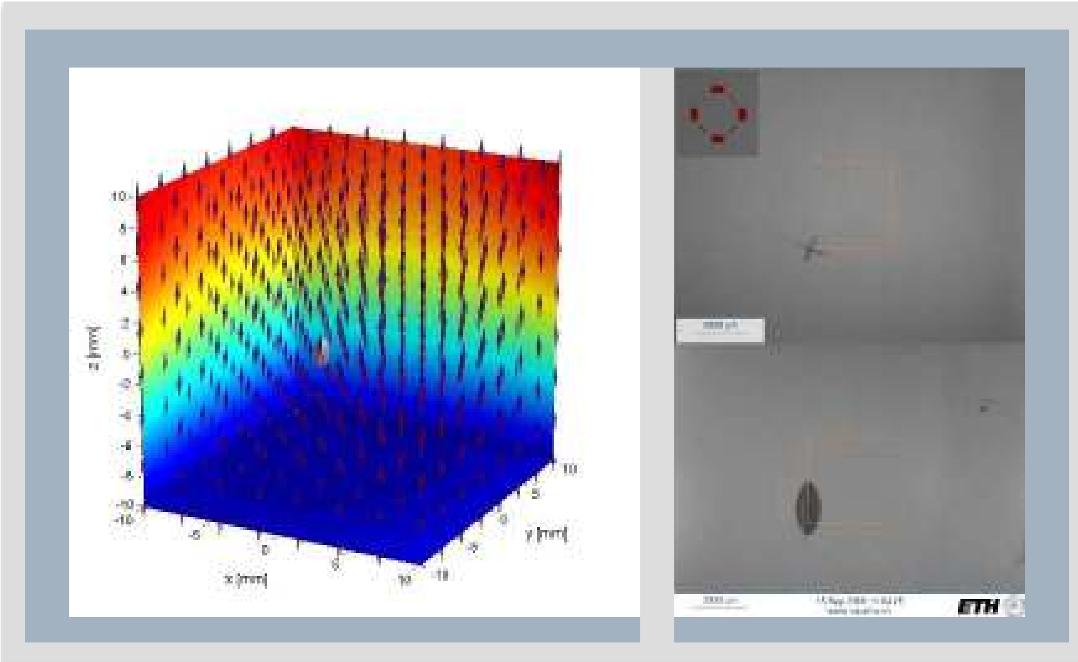


Wireless intraocular microrobots with surface coatings:

- Luminescence sensing,
- Oxygen sensor,
- Targeted drug delivery.

ELECTROMAGNETIC SYSTEM FOR 5-DOFS





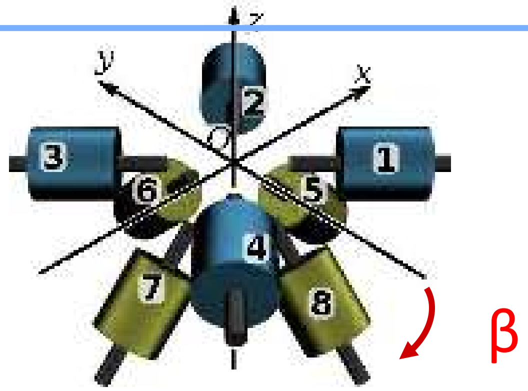
M. Kummer, J.J. Abbott, B.E. Kratochvil, R. Borer, A. Sengul, B.J. Nelson, “OctoMag: An Electromagnetic System for 5-DOF Wireless Micromanipulation“, *IEEE Transaction on Robotics*, Vol. 26, No. 6, Sept 2010.

- **Magnetic gradient based pulling**
  - Holonomic 5-DOF control
    - 3 axis translation, 2 axis orientation

$$\mathbf{T} = \upsilon \, \mathbf{M} \times \mathbf{B} \qquad \mathbf{F} = \upsilon \, (\mathbf{M} \cdot \nabla) \, \mathbf{B}$$

Workspace Analysis

Electromagnets Configuration



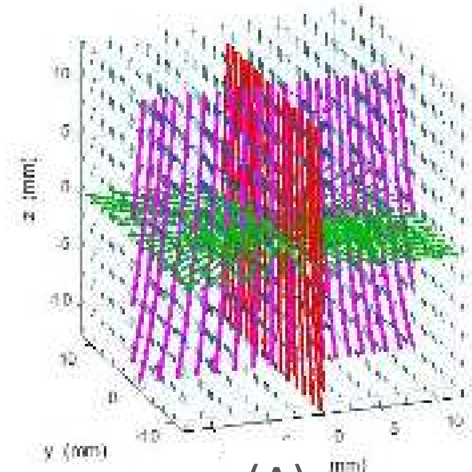
(A)

(1) **OctoMag** Configuration

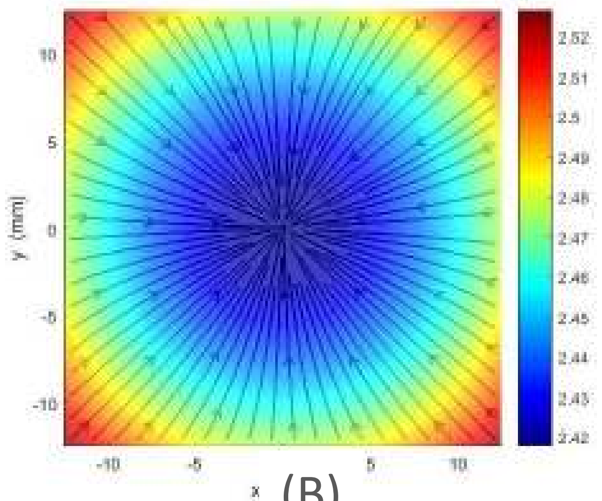
- Electromagnets 1-to-4; β=0°
- Electromagnets 5-to-8; β=45°

(2) **MiniMag** Configuration

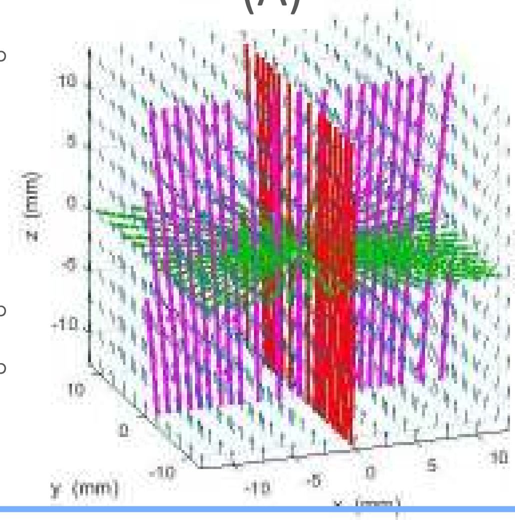
- Electromagnets 1-to-4; β= 42°
- Electromagnets 5-to-8; β= 62°



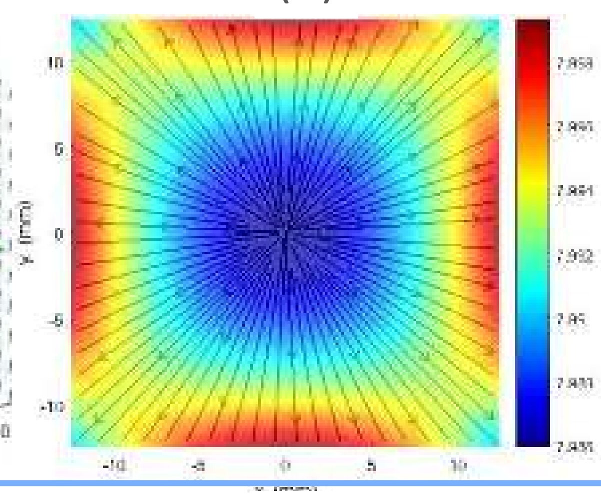
(A)



(B)



(C)

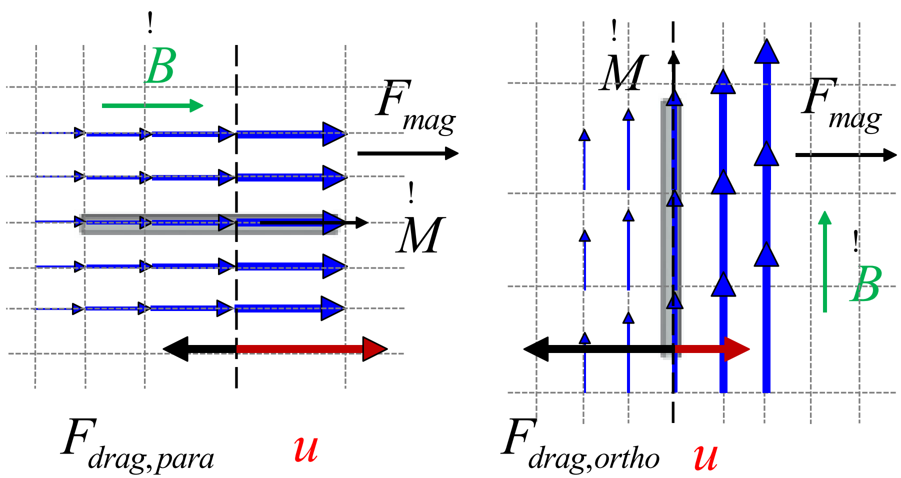


(D)

Magnetic Manipulation in Fluids

- **Magnetic gradient based pulling**
  - Holonomic 5-DOF control
    - 3 axis translation, 2 axis orientation

$$\mathbf{T} = \upsilon\, \mathbf{M} \times \mathbf{B} \qquad \mathbf{F} = \upsilon\, (\mathbf{M} \cdot \nabla)\, \mathbf{B}$$



- **Fluid dynamics at the small scale:**
  - Viscous forces dominate inertial forces

$$\mathrm{Re} = \frac{U \cdot L \cdot \delta}{\eta}$$

for $\mathrm{Re} << 1$:

$$\mathbf{F}_{drag} = -D \cdot \mathbf{u}$$

$$D_{sphere} = 6\pi\eta r$$

$$D_{cylinder,para} = \frac{4\pi\eta l}{\ln(2l/r) - 0.807}$$

$$D_{cylinder,ortho} = \frac{8\pi\eta l}{\ln(2l/r) + 0.193}$$

Stationary Electromagnets

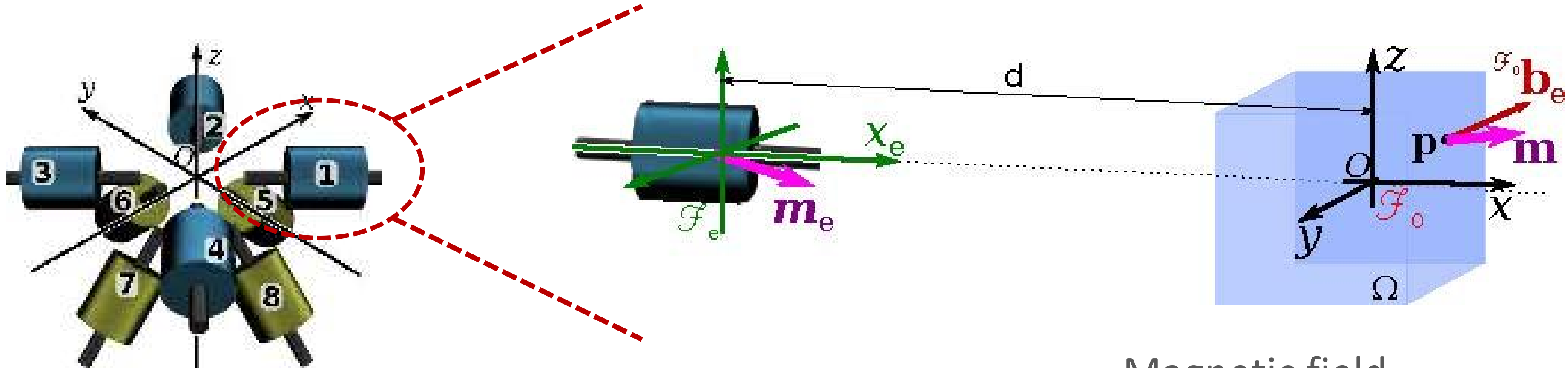
- **The advantages of static configurations**
  - Optimized for a specific application, such as OctoMag, MiniMag;
  - Simple configuration;

- **The disadvantages of static configurations**
  - Fixed workspace determined by electromagnets configuration;
  - Optimized performance only for the overall workspace;
  - Existing singular values cannot be removed close to the boundaries;
  - Manipulability depends on the position of the microrobot;
  - The control of a certain degree of freedom is achieved only by current.

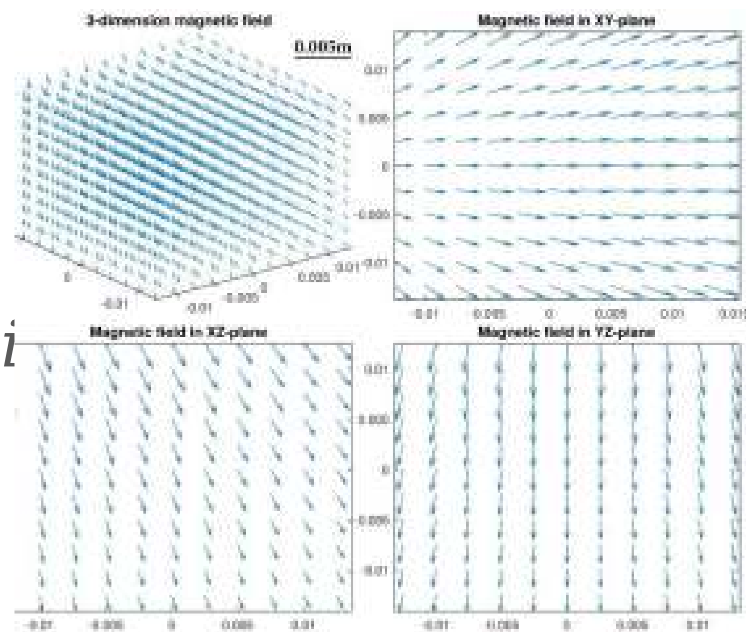
Solution: Combining stationary and mobile electromagnets

Model of Electromagnet

- Soft-magnetic-core electromagnet
  - Point dipole model



Magnetic field



Each electromagnet creates a magnetic field throughout the workspace that can be precomputed:

$$B(p,i) = \frac{\mu_0}{4\pi|p|^3}\left(\frac{3(\Gamma \bullet p)}{|p|^2} - \Gamma\right) \bullet i$$

MODEL OF ELECTROMAGNET

- **The magnetic field can be expressed in the reference frame $\mathcal{F}_o(O; x, y, z)$**

$$T^{\mathcal{F}_o}_{\mathcal{F}_e} = \begin{pmatrix} r^{\mathcal{F}_o}_{\mathcal{F}_e} & t^{\mathcal{F}_o}_{\mathcal{F}_e} \\ \mathbf{0} & \mathbf{1} \end{pmatrix}$$

Transformation matrix

$$ {}^{\mathcal{F}_e}B(p,i) = \frac{\mu_0}{4\pi|p|^3}\left(\frac{3(\Gamma \bullet p)}{|p|^2} - \Gamma\right) \bullet $$

Magnetic field on electromagnet frame

$$ {}^{\mathcal{F}_o}B(p,i) = T^{\mathcal{F}_o}_{\mathcal{F}_e} \cdot {}^{\mathcal{F}_e}B(p,i) $$

Magnetic field on reference frame

Magnetic Field and Gradient Generation

- **Magnetic field generated by n electromagnets with soft-magnetic cores**
  - Linear superposition of fields and gradients

(1)
$$\begin{cases} \mathbf{B}(\mathbf{P}) = \sum_{e=1}^{n} \mathbf{B}_e(\mathbf{P}) = \sum_{e=1}^{n} \tilde{\mathbf{B}}_e(\mathbf{P}) i_e \\ \mathbf{B}(\mathbf{P}) = \begin{bmatrix} \tilde{\mathbf{B}}_1(\mathbf{P}) & \cdots & \tilde{\mathbf{B}}_n(\mathbf{P}) \end{bmatrix} \begin{bmatrix} i_1 \\ \vdots \\ i_n \end{bmatrix} = \mathcal{B}(\mathbf{P}) \boldsymbol{I} \end{cases}$$

Operation of system with cores in their linear region

Field precomputed/measured *in situ.*

$$\begin{bmatrix} \mathrm{T} \\ \mathrm{F} \end{bmatrix} = \mathrm{A}_{\mathrm{T,F}}(\mathbf{M}, \mathbf{P}) I$$

$$V = J(\theta)\dot{\theta}$$

- **Torque and force generation**

(2)
$$\begin{cases} \begin{bmatrix} \mathbf{T} \\ \mathbf{F} \end{bmatrix} = \begin{bmatrix} Sk(\mathbf{M})\mathcal{B}(\mathbf{P}) \\ \mathbf{M}^T \mathcal{B}_x(\mathbf{P}) \\ \mathbf{M}^T \mathcal{B}_y(\mathbf{P}) \\ \mathbf{M}^T \mathcal{B}_z(\mathbf{P}) \end{bmatrix} \begin{bmatrix} i_1 \\ \vdots \\ i_n \end{bmatrix} = \mathcal{A}_{T,F}(\mathbf{M}, \mathbf{P}) \boldsymbol{I} \\ \boldsymbol{I} = \mathcal{A}_{T,F}(\mathbf{M}, \mathbf{P})^{\dagger} \begin{bmatrix} \mathbf{T}_{des} \\ \mathbf{F}_{des} \end{bmatrix} \end{cases}$$

- The mean index

$$\langle\varphi\rangle = \frac{1}{N}\sum_{p}^{N}\varphi(P)$$

- The uniformity index

$$\gamma(\varphi) = 1 - \frac{\sum_{P}^{N}|\varphi(P) - \langle\varphi\rangle|}{2N\langle\varphi\rangle}$$

- The manipulability index

$$\boldsymbol{\omega}(\mathbf{A}) = \sqrt{\boldsymbol{det}(\mathbf{A}\mathbf{A}^{T})} = \prod_{e=1}^{n}\boldsymbol{\sigma}_{e}$$

- The normalized manipulability

$$\boldsymbol{\omega}_{n} = \frac{\boldsymbol{\omega}(\mathbf{A}(\boldsymbol{m},\boldsymbol{p}))}{\max_{\boldsymbol{p}\in\boldsymbol{\Omega}}\boldsymbol{\omega}(\mathbf{A}(\boldsymbol{m},\boldsymbol{p}))}$$

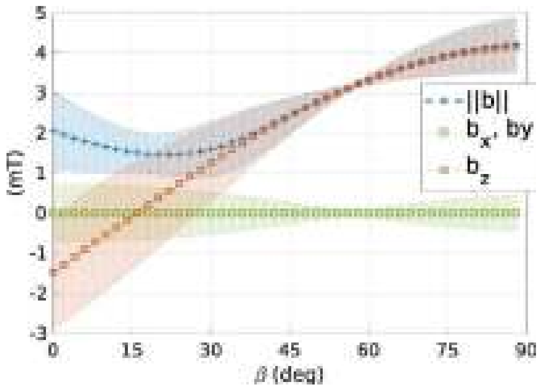
- The conditioning index

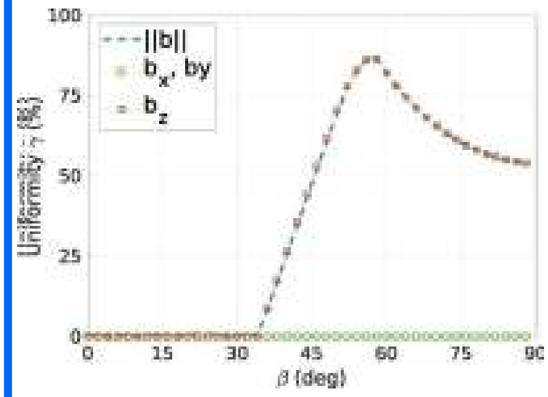
$$\mathbf{1}/\boldsymbol{k} = \boldsymbol{\sigma}_{\boldsymbol{min}}/\boldsymbol{\sigma}_{\boldsymbol{max}}$$

FOUR MOBILE ELECTROMAGNETS

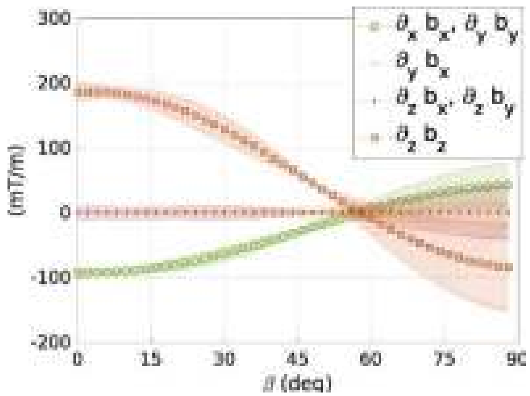
- Mobile angle changing in OctoMag-like structure

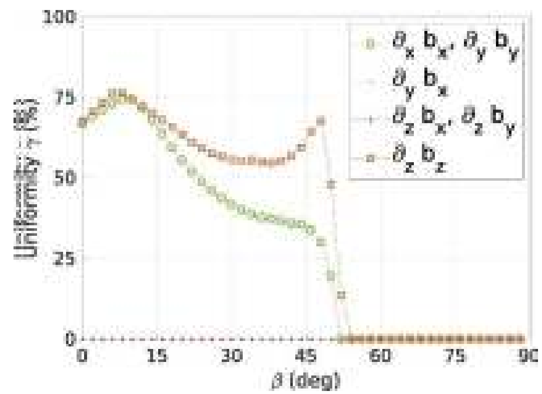
Magnetic Field





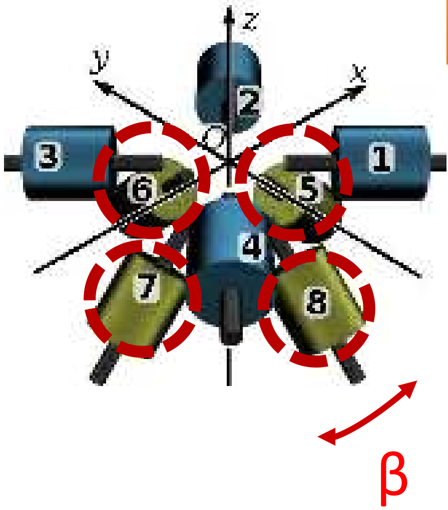
Magnetic Gradient





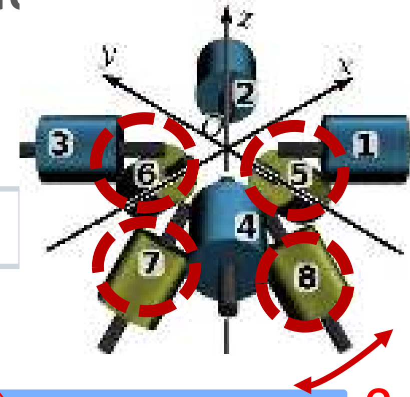
The Mean Value and The Standard Deviation Value

The Uniformity Index

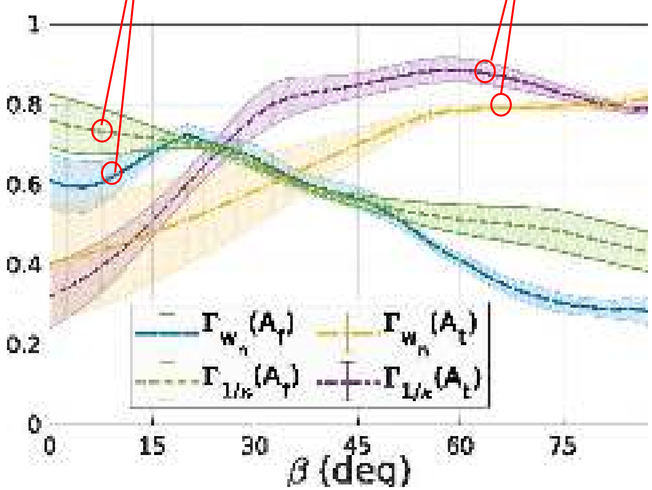


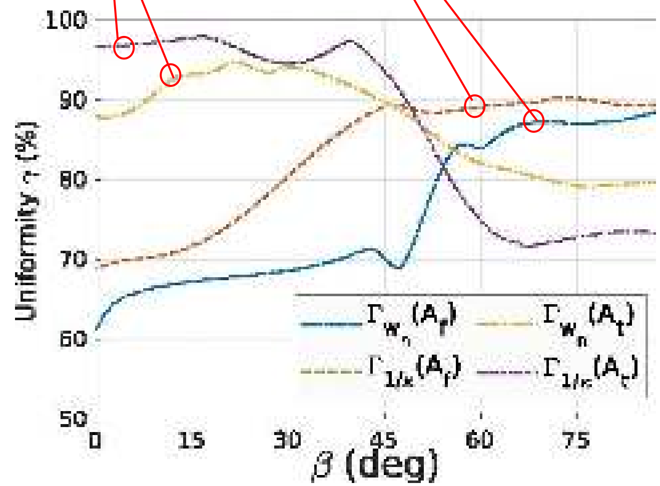
FOUR MOBILE ELECTROMAGNETS

- Statistical data of the global performance indexes of the force and torque performance analysis.



Force actuation | Torque actuation | Force actuation | Torque actuation



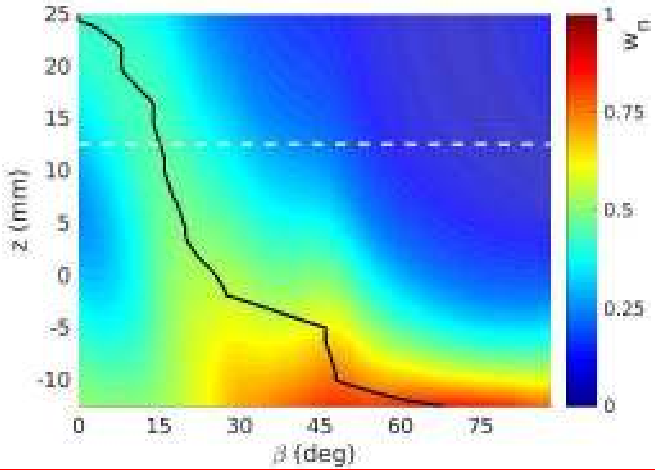


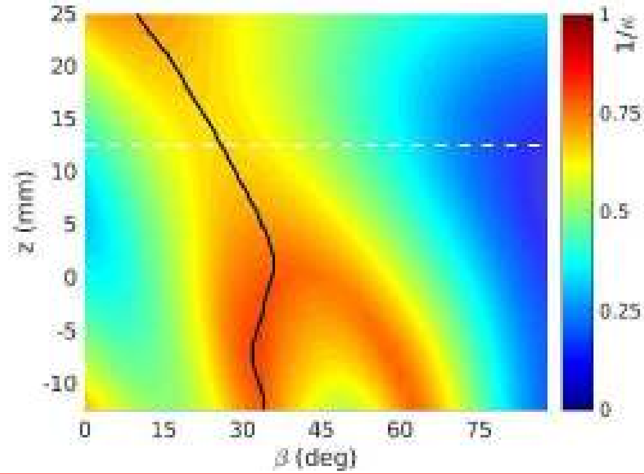
The mean and standard deviation	The uniformity value

FOUR MOBILE ELECTROMAGNETS

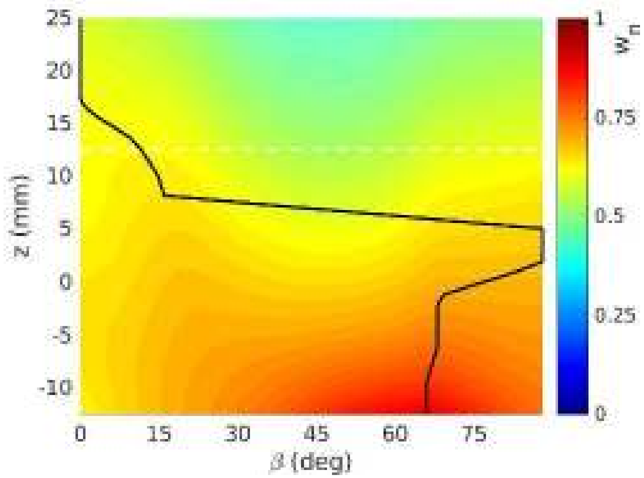
- Performance metrics along the Z-axis for mobile β

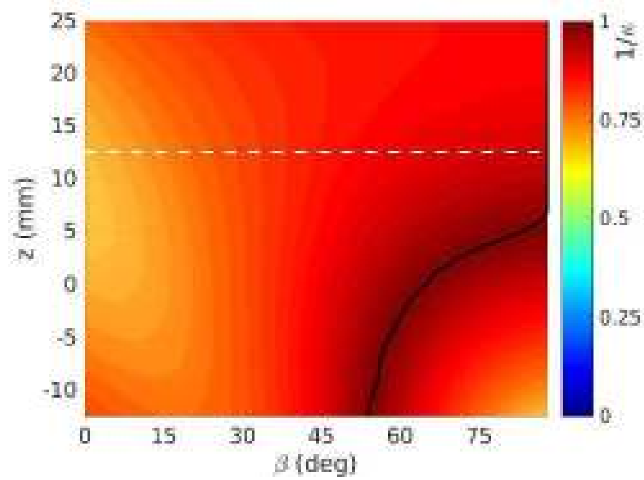
Magnetic Force





Magnetic Torque



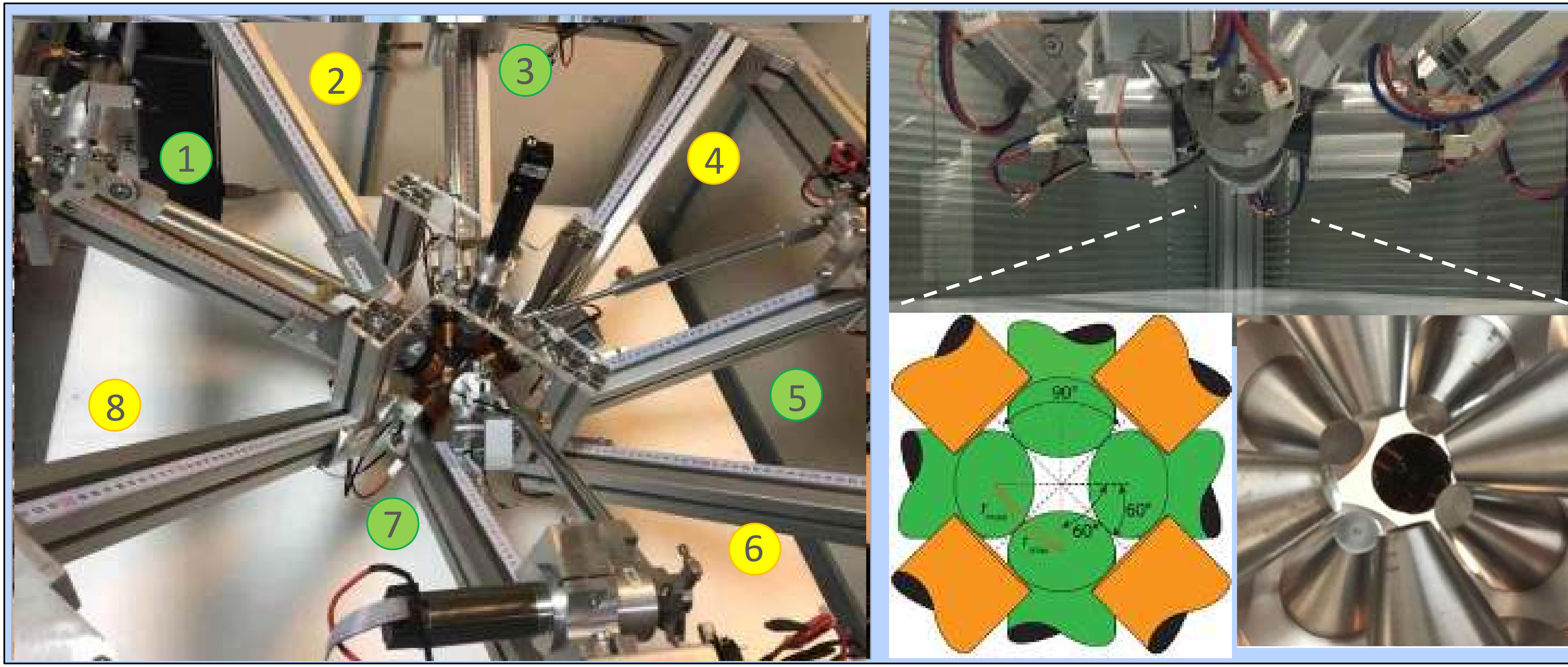


The Manipulability Index

The Conditioning Index

ROBOTIC EMA PLATFORM

Stationary arm   Rotating arm



- 8 electromagnets in inverted and non-inverted configurations
- Spherical workspace with a 20 mm diameter
- Up to 50 mT and 5 T/m
- Frequencies up to 2 kHz

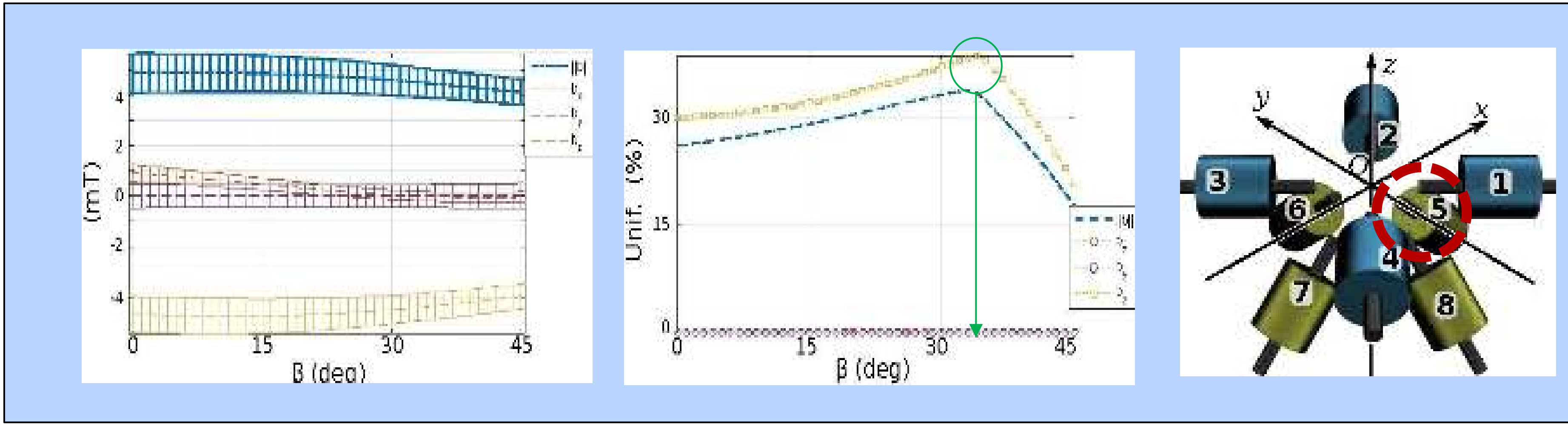
Mobile Electromagnets

- **The advantages of mobile configuration**
  - Change the local magnetic field distribution;
  - Strength variation of magnetic field by both current and position control;
  - Less singular values with same number of electromagnets;
  - More redundancy for control strategy;
  - Flexible system that will respect the geometry of human head, neck and shoulders;

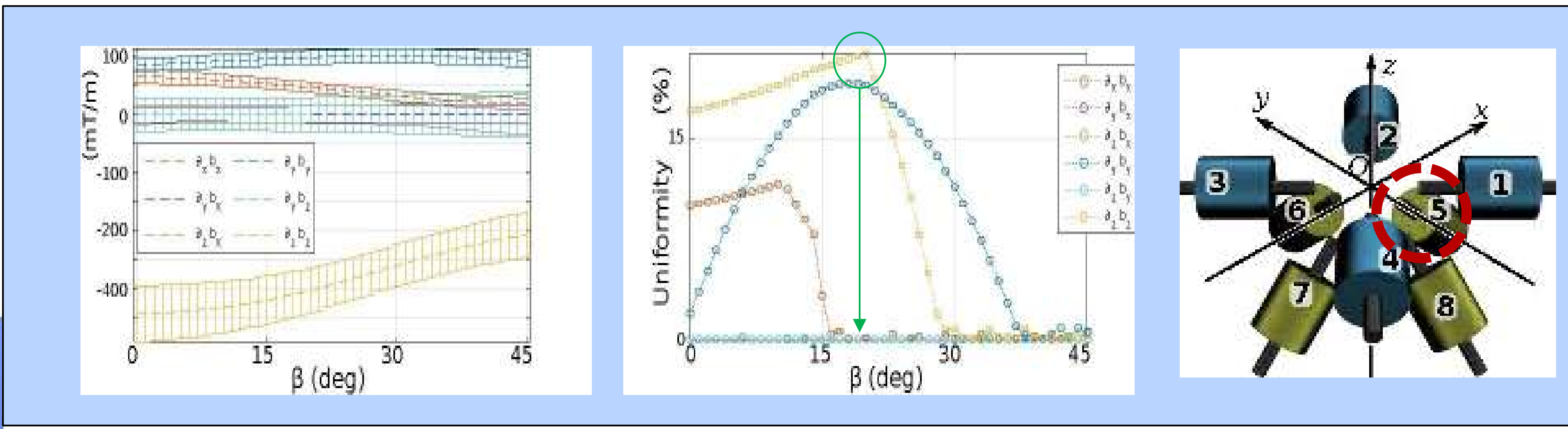
- **The disadvantage of mobile configuration**
  - More complicated to control both current and position of electromagnets;
  - How to choose dynamically the number and orientation of mobile electromagnets?

Solution: Performance metrics to quantify dynamically the best configuration.

ONE MOBILE ELECTROMAGNET

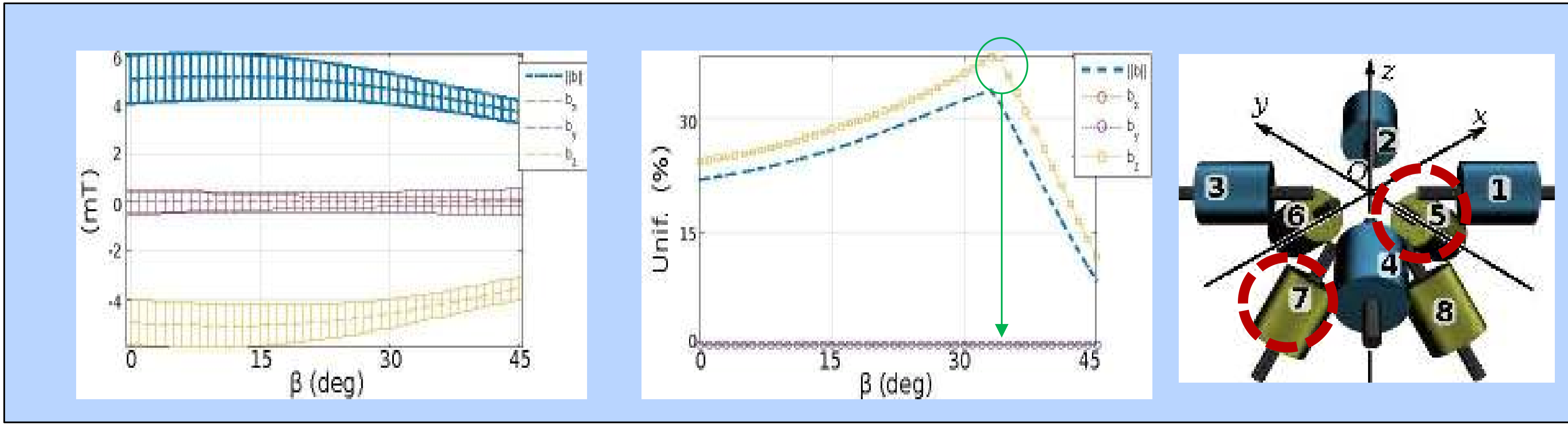


Magnetic fields (the mean and standard deviation)

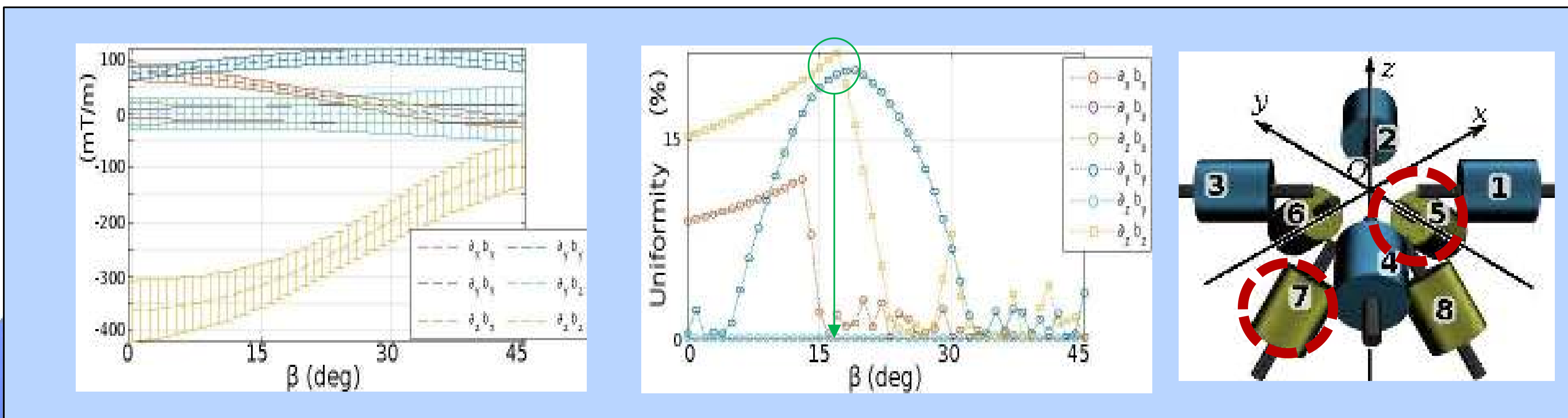


Magnetic gradients (the mean and standard deviation)

TWO MOBILE ELECTROMAGNETS (COILS 5 , 7)



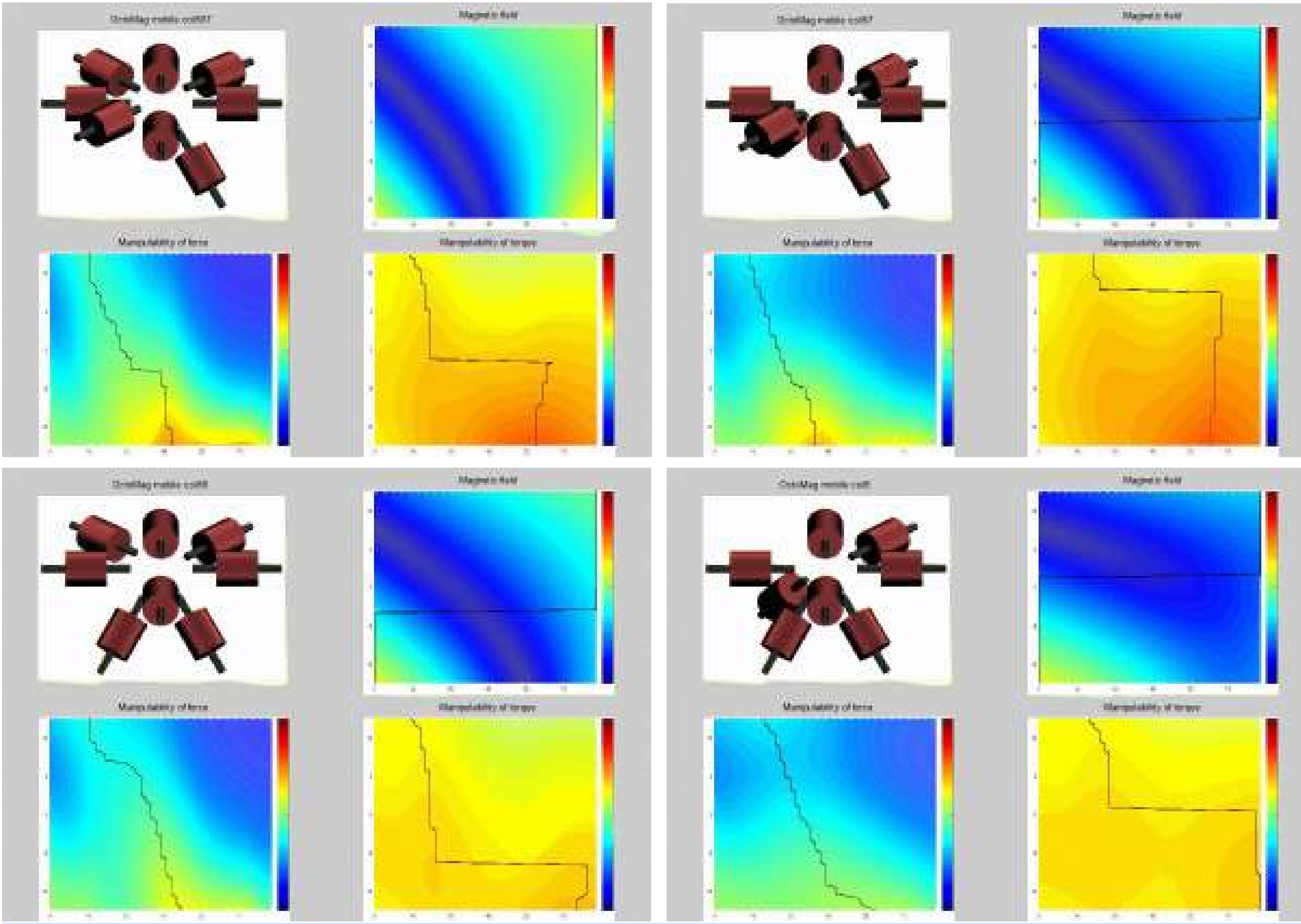
Magnetic fields (the mean and standard deviation)



Magnetic gradients (the mean and standard deviation)

PRISME

PERFORMANCE OF ROBOTIC EMA SYSTEM



Representation of the magnetic field, manipulability of force and manipulability of torque with different configurations respectively

CONCLUSION AND FUTURE WORKS

Validated works

- Optimization through modeling of a magnetic ophthalmology robotic platform.
- Validation of the magnetic actuation matrix $A_{T,F}$ (**M,P**)

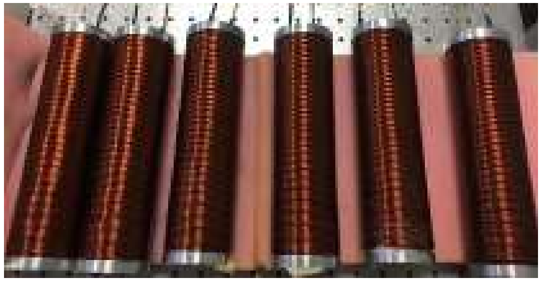
Undergoing works

- Experimental validation of performance matrices involving stationary and mobile electromagnets;

Future works

- Real-time control using deep learning methods ;
- Small animal tests using novel generation of coils.

$$\begin{bmatrix} T \\ F \end{bmatrix} = A_{T,F}(\mathbf{M},\mathbf{P})I$$



Thanks for your attention!