POLITECNICO DI TORINO

Master Degree Thesis

Design of a Micro-Robotic System with multi-stage Magnetic Actuation

Supervisors
Prof. Alessandro Rizzo
Prof. Arianna Menciassi
Ph.D. Veronica Iacovacci

Candidate
Michelangelo Barletta

Academic Year 2021/2022

Abstract

In the last 10 years many researches explored the application of endoscopic capsules or flexible endoscopes to apply for in vivo experiments for future applications on the medicine. That's because there will be an easier accessibility to tiny and complex environments due to their small-scale dimensions. Now, microrobotic capsules can be used to operate down to the cellular or sub-cellular scale, allowing efficient in vitro interactions in order to move and sort cells. In vivo applications of microrobots are especially applied in minimally-invasive surgery, including: targeted drug delivery, brachytherapy, hyperthermia etc. These are even smaller than the endoscopic ones, allowing freer movement in smaller workspace. To do this, the capsules are equipped with nanoparticles to be released through a proper release mechanism in order to reach specific area of the human body.

The main purpose of the Thesis is the analysis of the actuation of millimetric capsules, magnetized by an Internal Permanent Magnet, through an external magnetic field properly generated by an External Permanent Magnet. Moreover, another smaller capsule containing Neodymium-Iron-Boron (NdFeB) particles is used to simulate the interaction between the nanoparticles and the magnetic capsule after their release establishing a wireless link between them. Hence, a multi-stage magnetic control is developed. A simulated scenario for the application of the microrobotic capsule is created computing, with a Matlab code, the magnetic field, force and torque generated by the system for different distances to compare them with the real values sensed by the Infineon TLE493D sensor. The inverse problem is considered computing the distance of a magnetic object starting from the magnetic field generated by it.

Acknowledgements

I would like to express my gratitude to Professors Arianna Menciassi and Alessandro Rizzo, whose professionality in providing feedbacks led me to this.

Furthermore, I want to thank my co-supervisor, Dr. Veronica Iacovacci who guided me since the beginning of this thesis, always available in monitoring the work with useful suggestions and assistance. I also appreciate all the support I received by the members of the Surgical Robotics and Allied Technologies Area of the BioRobotics Institute during my stay, which guided and encouraged me like a longtime colleague.
My deepest gratitude go to all of my family members for their encouragement and support throughout my studies, without which this would not have been possible. Lastly, I would like to thank all my friends who supported me during this journey, especially I want to thank Cosimo and Silvia for being always patient during our meals.

Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Introduction

The goal of this Thesis is to propose a multi-stage magnetic actuation to control millimetric magnetic capsules, equipped with Internal Permanent Magnets (IPM) or Ferromagnetic powder, through an external magnetic field produced by an External Permanent Magnet (EPM). The theoretical studies on electromagnetism are able to give informations about the magnetic field that a magnetic object is able to produce. This strongly depends on the type of magnet analised, that can be a Permanent Magnet or an Electromagnet, but also on their dimensions. There are different actuation methods that have been used to control small capsules inside the human body. However, in order to reach a good balance between the ease of control and the health safety, the magnetic one is considered the best choise. The recent researches about in-vitro and in-vivo applications of microrobotic capsules explored the possibility to reach specific areas of the human body through nanoparticles considered as drugs and have less and less invasive treatments. In the proposed approach, the External Permanent Magnet is a cylindrical magnet managed by the Mitsubishi Robotic Manipulator RV-3SB as its end-effector allowing a variety of movements to take into account. Moreover, these are extended considering two different arrangements of the magnet: Horizontal and Vertical. In particular, the analysis of the magnetic field produced by a magnetic object is done according to the Dipole-Dipole approximation that considers a magnetic element as a dipole when its dimension is much smaller than the distance from the source. Thanks to this, the magnetic force and torque produced can be computed through the field gradient. Moreover, a local actuation method is explored considering the presence of coils around the capsule to be actuated. In this case the Biot-Savart Law is the best choice to compute all the magnetic quantities in the system. Some Matlab codes are used to perform all the computations to find the values of magnetic field, force and torque, expected in the entire system. These values allow a comparison with the real values sensed by the magnetic field sensor Infineon TLE493D in order to study an implementation of simulated scenarios for safer study and experiments in the future.

1.2 Thesis Outline

This Thesis is organized as follows: in chapter 2, the state of the art of the micro-robotic capsules is presented, including different possible actuation methods, as well as a short description about the nanoparticles that can be used to have the targeted treatments in the future. In chapter 3 the most relevant theoretical notions about the electromagnetism are provided, with an in-depth analysis of the computations about the magnetic quantities according to specific approximation that can be done. In chapter 4, the overall system is described to understand how the Manipulator is managed and what kind of capsules there can be. In chapter 5, the actuation methods of the micro-robotic capsules are analysed, with distinct descriptions depending on the type of capsule to be actuated. In chapter 6, the theoretical values computed are compared to the real ones sensed to highlight their differences. Finally, in chapter 7, conclusions are drawn, along with a discussion about possible further improvements. At the end of the thesis, in Appendix A the Matlab code to implement the theoretical background is shown, while in Appendix B there is the Matlab code to do an inverse solution of the problem (from the results to the data).

Chapter 2

State of the Art

Microrobotic is a modern technology that allows to built very small robot for different purposes. The research areas involved are many, like the Medical one, for targeted surgery, drug delivery, diagnostics, but also Monitoring, to check the environments. That's why it is also important to check the biological compatibility of the materials in order to avoid toxicity and to do safer operations in the human body.

A way to have less and less invasive surgery is still a long-standing problem for the modern Medicine. Microrobotic represents a valid solution since microrobots can use the natural pathways in the human body, like blood vessels or gastrointestinal tract, for diagnosis and treatment, to deliver drugs to a particular area of the body. In order to perform these tasks in a better way, it is possible to use microscopic capsules, managed like microrobots, with a swarm of nanoparticles inside them. So that, a microscopic capsule can be moved in the human body, releasing the nanoparticles in the specific area that must be treated.

Researchers have used different actuation systems to have custom-designed workspace and multiple degrees of freedom (DoF) to actuate microrobots with various motion control methods. In particular, the actuation can be acoustic, optical, magnetic etc. The best choice for the actuation seems to be the magnetic one, since it allows to have a large working space, precise and controllable large-scale operating force, small biological tissue influence, and low dependence on external energy lines.

2.1 Magnetic Field

To better understand how the magnetic field can be the right choice to control a microrobot, it is necessary to explain what is a magnetic field.

A magnetic field is a vector field in the neighbourhood of a magnet, electric current or charging electric field in which a magnetic force is observable. The magnetic field is represented by vectors that have both direction and magnitude. In particular, there is the Magnetic Flux Density **b**, measured in T, and the Magnetic Flux Strength **h**, measured in A/m, that differ for the magnetization.
Considering the vacuum:

$$\frac{\mathbf{b}}{\mu 0} = \mathbf{h} \tag{2.1}$$

Another important element is the magnetic moment. It can be defined as a vector relating the aligning torque on the object from an externally applied magnetic field to the field vector itself. It is indicated as **m**. This can be computed considering the remanence **Mr** or the residual flux density **Br** and the volume of the magnet V:

$$\mathbf{m} = \frac{1}{\mu 0} * \mathbf{Br} * V \tag{2.2}$$

$$\mathbf{m} = \mathbf{Mr} * V \tag{2.3}$$

Moreover, it is possible to compute the force and the torque generated by the field:

$$\boldsymbol{\tau} = \mathbf{m} \times \mathbf{b} \tag{2.4}$$

$$\mathbf{f} = \nabla(\mathbf{b} \cdot \mathbf{m}) \tag{2.5}$$

2.2 Systems for Manipulation and Actuation

Considering a magnetic actuation of the microrobot, it is necessary to understand how to generate the external magnetic field and how to use it to control the capsule inside the human body.

2.2.1 Permanent Magnets

It's an object made from a material that is magnetized and creates its own persistent and strong magnetic field which can be controlled by translating and/or rotating these sources. Moreover, the effects of translation and rotation on the field and field derivative are nonlinear, so the control of these systems can be achieved using nonlinear solution methods. These sources are commonly modeled as point dipoles, which is quite accurate even for nonspherical magnets like cylinders etc.

A general actuation system using permanent magnets would move the six-DOF pose of each actuating magnet. However, the ability to fully control the poses of the magnets will be mediated by the robotic positioning system.

To do this, it can be used a single actuating magnet, mounted on a six-DOF robotic arm such that its full position and orientation can be controlled within the workspace of the robot arm. This approach creates a very large actuation workspace that is limited only by the reach of the robot arm.

2.2.2 Electromagnets

An electromagnet is made from a coil of wire that acts as a magnet when an electric current passes through it but stops being a magnet when the current stops. Often, the coil is wrapped around a core of "soft" ferromagnetic material such as mild steel, which greatly enhances the magnetic field produced by the coil.

Electromagnets can also be moved through space to vary magnetic inputs to a robotic system. There exist also systems that have combined specialized coils, in various arrangements, with the capability to move one or more of the coils in order to increase the DOFs of control.

2.2.3 Existing system

Now, considering the magnetic field that must be produced externally to control the capsule, it is possible to choose between the two types of magnets exposed before.

In particular, two tables are exposed below to better understand what kind of systems have been used in the researches and what kind of environment is set. In this tables, the magnetic field is distinguished into Gradient, responsible of the magnetic force (G) and Uniform, responsible of the torque (U). The number of Electromagnets or Permanent Magnets (EM and PM) used for the different systems is highlighted on the 'Type' column of the two tables, but it is also possible to see the Control DoF of an object in that system. Finally, the magnetic field and gradient used and the Workspace and Microrobot dimension are specified.

Type	**DOF Magnetic**	**DOF Control**	**Workspace**	**Microrobot dimension**	**Magnetic Field and Gradient**
Helmotz [1] 6 EM	3 DOF (U) 1 DOF (G)	3 DOF	56 x 56 x 56 mm	Spherical 5mm P.M.	40 mT and 250 µT/mm
Octo-Mag [2] 8 EM	3 DOF (U+G)	5 DOF	Semi-sphere 25 mm	500 - 2000μm	15 mT
Bat-Mag [3] 9 EM	6 DOF (U+G)	6 DOF	35 x 35 x 35 mm	Up to 3mm	160 mT and 3.6 T/m
Mobi-Mag [4] 4 EM	/	/	18 x 18mm	Up to 4mm	15 mT and 60 mT/m
Diller et al. [5] 8 EM	6 DOF (U+G)	6 DOF	20 x 20 x 20 mm	400 - 4000μm	8.3 mT and 0.34 T/m
Rahmer et al. [6] 18 EM	3 DOF (UR+G)	5 DOF	Sphere 20 cm	Diameter 4mm Length 10mm	400mT vert. and 2 T/m, 100mT horiz.
Niu et al. [7] 6 EM	6 DOF (U+G)	6 DOF	Sphere 110 mm	5 - 15 μm	40mT and 250 mT/m

Table 2.1: Electromagnetic systems

Type	**DOF Magnetic**	**DOF Control**	**Workspace**	**Microrobot dimension**	**Magnetic Field and Gradient**
External Rotating Permanent Magnets [8] 4 RPM	1 DOF (G)	6 DOF	60 x 60 x 70 mm	Cylindrical 30 x 30mm	30 mT
External Permanent Magnet, Robotic Manipulator [9]	6 DOF	5 DOF	40 x 40 x 40 mm	Cylindrical 24 x 9.5mm	100 mA/m

Table 2.2: Permanent Magnets systems

2.3 Micro-robotic capsules

As said before, the micro-robotic capsule inside the human body can be controlled through a magnetic field generated externally. To do so, an internal magnet or a wrapped coil is required.

First of all, a micro-robot is a robot with dimensions of the order of micron. It can have different shapes, but the preferred is the capsule or pill one since it can be controlled in a homogeneous way and it may contain a swarm of nanoparticles (drugs, cells etc.) inside to use for specific treatments.

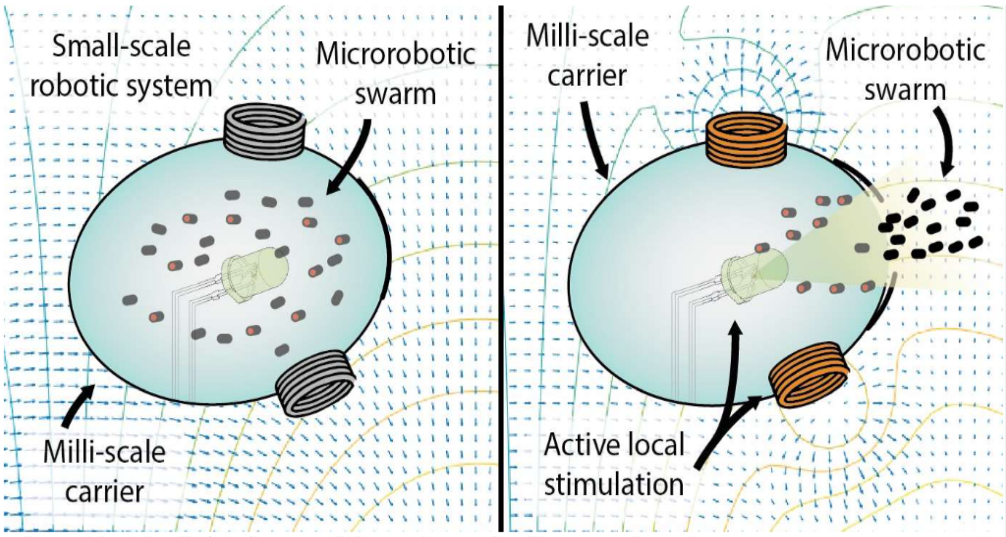


Figure 2.1: Capsule

Considering a little permanent magnet inside the capsule, it can be used a dipole-dipole interaction with the external magnet. So that, the magnetic field can be computed using the Magnetic Field Dipole Approximation.

On the contrary, a coil can be used to interact with the external permanent magnet when there is an electric current inside the wire, so the magnetic field will be computed using the Biot-Savart Law.

Both of the two methods above depend on the distance between the external permanent magnet and the internal one or the coil around the capsule.

2.4 Nanoparticles

The nanoparticles inside the capsule can be defined as particles with 1 to 500 nanometers in diameter. In particular, thanks to their very small dimensions, they are more subject to the brownian motion, that is a random motion and so they cannot sediment.

The synthesis of a nanoparticle is called nucleation. This process has a big influence on its properties, since it can define the dimension, shape etc.

One of the main issue of encapsulated nanoparticles is the way to control them. A possible solution can be to use nanomagnets that can be controlled through the magnetic field generated by the capsule.

The Bio-compatibility is a key factor for biomedical applications, and this is valid also for the nanoparticles. The nanotoxicology is the study of the toxicity of the nanomaterials. This can refer to respiratory hazards, or dermal and gastrointestinal ones [10]:

- Respiratory: The inhalation of nanoparticles can be very easy and it can lead to their deposition in the lungs, but also to their movement, thanks to the bloodstream, to other organs. A toxic material can be responsible for tumors, inflammations, cardiovascular problems etc.
- Dermal: There can be also the possibility of a penetration inside the skin of the nanoparticles after exposure. This may cause inflammation, but this is still under study.
- Gastrointestinal: Ingestion can occur from unintentional hand-to-mouth transfer of materials; this has been found to happen with traditional materials, and it is scientifically reasonable to assume that it also could happen during handling of nanomaterials. Ingestion may also accompany inhalation exposure.

Chapter 3

Theoretical Background

As said in the chapter before, a magnetic actuation can be considered as a good choice to control capsules for targeted drugs delivery. However, the magnetic field used to control it can be produced considering two different methods.

3.1 Permanent magnets: Dipole-Dipole

A stable magnetic field is crucial in order to have a good control of very small objects, but also for tracking systems. A permanent magnet is able to create a persistent magnetic field, so it can be used in stationary conditions. So that, a permanent magnet is used to produce a stable external magnetic field, but it can also be inside the capsule to make it magnetic.

The interaction between an external permanent magnet and an internal one inside the capsule is considered as a dipole-dipole interaction since the distance between the two objects is much larger than the dimension of the themselves.

Actually, a distance bigger than the size of the object can be a problem, since the field generated by a magnet with an increasing distance, whether it be an electromagnet or an object made of magnetized material, make the object to shrink down to a point, and it becomes difficult to see the field shape that are due to the specific geometry of the magnet self [11].
However, the field flux density, generated by a magnetic dipole **m** from a point **Pm**, denoted as **b** at a point **Pb** can be described with the following equation:

$$\mathbf{b} = \left(\frac{\mu 0}{4\pi \|\mathbf{Pb} - \mathbf{Pm}\|^5} (3(\mathbf{Pb}-\mathbf{Pm})(\mathbf{Pb}-\mathbf{Pm})^T - \|\mathbf{Pb}-\mathbf{Pm}\|^2 I_3) \right) \mathbf{m} \quad (3.1)$$

Considering the distance between the magnetic dipole and the point in which the field is sensed, it is possible to denote:

$$\mathbf{r} = \mathbf{Pb} - \mathbf{Pm} \quad (3.2)$$

In the Figure 2.1 it is possible to see the magnetic dipole representation with the distance, magnetic field and magnetic moment vectors:

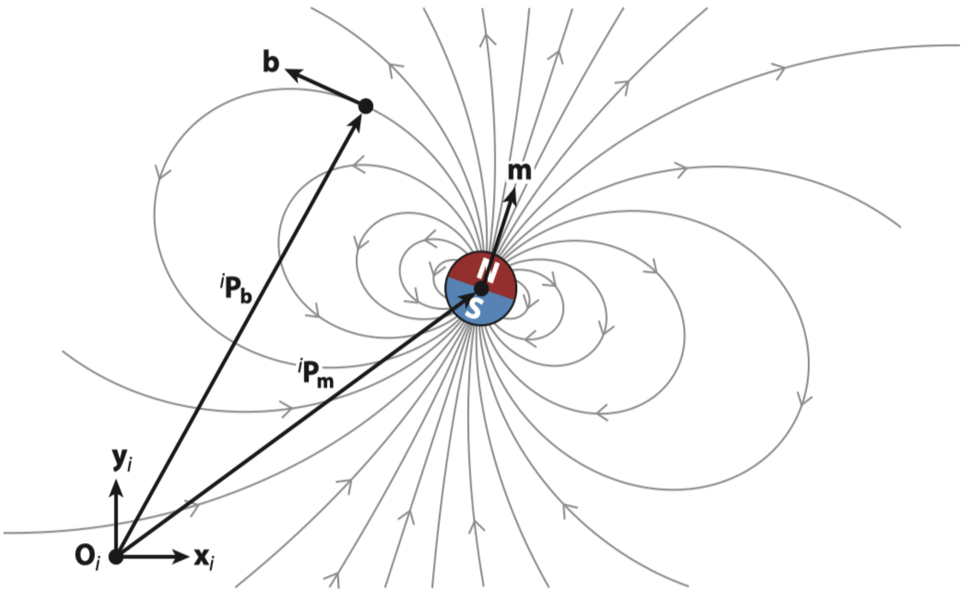


Figure 3.1: Magnetic Dipole Representation

Now, with suitable approximations, the dipole relationship can be represented as:

$$\mathbf{b} = \left(\frac{\mu 0}{4\pi \|\mathbf{r}\|^3} (3\hat{\boldsymbol{r}}\hat{\boldsymbol{r}}^{\boldsymbol{T}} - I_3) \right) \mathbf{m} \quad (3.3)$$

Where:

$$\hat{\boldsymbol{r}} = \frac{\mathbf{r}}{\|\mathbf{r}\|} \tag{3.4}$$

Considering these equations it is possible to highlight that the strength of a dipole field decays cubically with distance. At any given distance from the dipole, the field is twice as strong along the axis of the dipole as it is along the axes orthogonal to the dipole.

Actually, the discussion above considers the field of a magnet viewed from infinitely far away. However,if the point considered is close to the magnet it cannot reasonably be modeled as existing at a point, and the dipole model loses accuracy.

3.2 Electromagnets: Coils

Similarly, the magnetic field needed can be produced by a conductor with a current flowing in it. To compute the magnetic field **b** generated at any position **Pb** due to an electric current **i** flowing through a conductor, the Biot–Savart law is used considering the differential field component d**b** due to the current flowing through a differential length d**l** of the conductor at one specific location **Pdl**. Integrating the effect of each point along the length of the conductor, the magnetic field at **Pb** is:

$$\mathbf{b} = \int d\mathbf{b} = \int \mu 0 \frac{i d\mathbf{l} \times (\mathbf{Pb} - \mathbf{Pdl})}{4\pi \|\mathbf{Pb} - \mathbf{Pdl}\|^3} = \frac{\mu 0 i}{4\pi} \int \frac{S(\mathbf{Pb} - \mathbf{Pdl})}{\|\mathbf{Pb} - \mathbf{Pdl}\|^3} d\mathbf{l} \tag{3.5}$$

The notation $\mathrm{S}(\mathbf{v})$ indicates the skew-symmetric matrix packing of a vector used in the cross-product operation, which takes the form:

$$\mathrm{S}(\mathbf{v}) = \begin{bmatrix} 0 & -v_z & v_y \\ v_z & 0 & -v_x \\ -v_y & v_x & 0 \end{bmatrix}$$

However, considering a coil with multiple wraps the formula considered is:

$$\mathbf{b} = \frac{\mu 0 N i}{2} \frac{R^2}{R^2 + \sqrt{(\mathbf{Pb} - \mathbf{Pdl})^2}^3} \tag{3.6}$$

In this case, the magnetic field is proportional to the number of wraps of the wire, but also to the radius of the coil itself.

Actually, the magnetic field produced by a millimetric coil will be very low, so this method can be used to have local actuation near the capsule with an external wrapped coil.

3.3 Force and Torque on a Magnetic Dipole

Magnetic objects are subjected to a magnetic field generated by a source. This can be shown through forces and torques.

When a permanent-magnet or electromagnet dipole m is placed in an applied magnetic field b, the magnetic dipole is forced to translate and rotate in order to to minimize its magnetic energy. This can be seen as a generation of forces and torques in an attempt to increase, through translation and rotation, the magnetic energy:

$$E = \mathbf{b} \cdot \mathbf{m} \tag{3.7}$$

Considering the force, if a translation of **m** in a given direction increases this energy, then a magnetic force will be generated in that direction. Since only pure translations of the dipole are considered during the force calculation, m can be considered as constant. So that, considering the x-direction:

$$f_x = \frac{\partial(\mathbf{b} \cdot \mathbf{m})}{\partial x} = \frac{\partial(\mathbf{b}^T \mathbf{m})}{\partial x} = \frac{\partial \mathbf{b}^T}{\partial x}\mathbf{m} \tag{3.8}$$

This is valid for the three directions:

$$\mathbf{f} = \nabla(\mathbf{b} \cdot \mathbf{m}) = \begin{bmatrix} \frac{\partial \mathbf{b}}{\partial x} & \frac{\partial \mathbf{b}}{\partial y} & \frac{\partial \mathbf{b}}{\partial z} \end{bmatrix}^T \mathbf{m} = \begin{bmatrix} m_x \frac{\partial b_x}{\partial x} + m_y \frac{\partial b_y}{\partial x} + m_z \frac{\partial b_z}{\partial x} \\ m_x \frac{\partial b_x}{\partial y} + m_y \frac{\partial b_y}{\partial y} + m_z \frac{\partial b_z}{\partial y} \\ m_x \frac{\partial b_x}{\partial z} + m_y \frac{\partial b_y}{\partial z} + m_z \frac{\partial b_z}{\partial z} \end{bmatrix} \tag{3.9}$$

However, to use this formula, it is necessary to make some assumptions: generally, for robotics applications the electrostatic contribution in the Maxwell's equations, that explain how the magnetic field and the electric field are coupled, are negligible, so it is possible to write:

$$\nabla \cdot \mathbf{b} = 0 \implies \frac{\partial b_x}{\partial x} + \frac{\partial b_y}{\partial y} + \frac{\partial b_z}{\partial z} \tag{3.10}$$

Furthermore, it is possible to assume that there is no current flowing, so:

$$\nabla \times \mathbf{b} = 0 \implies \frac{\partial b_z}{\partial y} = \frac{\partial b_y}{\partial z}, \frac{\partial b_x}{\partial z} = \frac{\partial b_z}{\partial x}, \frac{\partial b_y}{\partial x} = \frac{\partial b_x}{\partial y} \tag{3.11}$$

Moreover, it can be considered the notation:

$$B_{\nabla} = \begin{bmatrix} \frac{\partial \mathbf{b}}{\partial x} & \frac{\partial \mathbf{b}}{\partial y} & \frac{\partial \mathbf{b}}{\partial z} \end{bmatrix} \tag{3.12}$$

Now, let's consider the torque. If a rotation of $\mathbf{m}$ about a given axis increases the energy, then a magnetic torque will be generated about that axis. If $\mathbf{m}$ is rotated from $\mathbf{b}$ by an angle θ_x about the x axis, the restoring torque about the x axis is:

$$\tau_x = \frac{\partial(\mathbf{b} \cdot \mathbf{m})}{\partial \theta_x} = \frac{\partial(\|\mathbf{b}\|\|\mathbf{m}\| \cos \theta_x)}{\partial \theta_x} = -\|\mathbf{b}\|\|\mathbf{m}\| \sin \theta_x \tag{3.13}$$

Combining the results for the individual components:

$$\boldsymbol{\tau} = \mathbf{m} \times \mathbf{b} = S(\mathbf{m})\mathbf{b} \tag{3.14}$$

3.4 Force and Torque between Magnetic Dipoles

In the previous section it was considered a magnetic dipole in an arbitrary magnetic field. However, if the field is produced by another dipole the formulas can be more specific:

The field-derivative matrix at location $\boldsymbol{P_j}$, generated by a dipole $\boldsymbol{m_i}$ located at $\boldsymbol{P_i}$, is:

$$\boldsymbol{B_\nabla} = \frac{3\mu 0}{4\pi\|\boldsymbol{r_{ij}}\|^4}\left(\boldsymbol{m}_i\hat{\boldsymbol{r_{ij}}}^T + \hat{\boldsymbol{r_{ij}}}\boldsymbol{m_i}^T + (\hat{\boldsymbol{r_{ij}}}^T\boldsymbol{m_i})(I_3 - 5\hat{\boldsymbol{r_{ij}}}\boldsymbol{r_{ij}}^T)\right) \tag{3.15}$$

The force generated is:

$$\boldsymbol{f} = \frac{3\mu 0}{4\pi\|\boldsymbol{r_{ij}}\|^4}\left((\hat{\boldsymbol{r_{ij}}}^T\boldsymbol{m}_j)\boldsymbol{m_i} + (\hat{\boldsymbol{r_{ij}}}^T\boldsymbol{m}_i)\boldsymbol{m}_j + (\boldsymbol{m_i}^T\boldsymbol{m_j} - 5(\hat{\boldsymbol{r_{ij}}}^T\boldsymbol{m_i})(\hat{\boldsymbol{r_{ij}}}^T\boldsymbol{m}_j)\right)\hat{\boldsymbol{r_{ij}}} \tag{3.16}$$

The torque generated is:

$$\boldsymbol{\tau} = S(\boldsymbol{m_j})\boldsymbol{b} = S(\boldsymbol{m_j})\left(\frac{\mu 0}{4\pi\|\boldsymbol{r_{ij}}\|^3}(3\hat{\boldsymbol{r_{ij}}}\boldsymbol{r_{ij}}^T - I_3)\right)\boldsymbol{m_i} \tag{3.17}$$

3.5 Magnetic moment and Magnetization

In the previous chapter the magnetic moment was defined as a vector relating the aligning torque on the object from an externally applied magnetic field to the field vector itself. It is indicated as **m**. This can be computed considering the remanence **Mr** or the residual flux density **Br** and the volume of the magnet V:

$$\mathbf{m} = \frac{1}{\mu 0} * \mathbf{Br} * V \tag{3.18}$$

$$\mathbf{m} = \mathbf{Mr} * V \tag{3.19}$$

Now, it is possible to figure out how the magnetization of a magnetic object can be represented as a property that expresses the density of permanent or induced magnetic dipole moments in a magnetic material.

The Magnets used in robotics are large enough that is possible to assume it as a polycrystalline object with many randomly oriented grains,such that shape anisotropy (i.e.,the effect of geometry) dominates over crystalline anisotropy in determining magnetization.

Typically the ferromagnetic materials are used since they can be strongly influenced by the presence of a magnetic field. In fact, an applied field causes the contributions of the electrons to organize, resulting in a net magnetization that is nonzero. Also, their magnetization will remain even in the absence of an external field.

Let's consider to the magnetic field strength within the magnetic material as $\boldsymbol{h_{in}}$. At any given location in the material, the magnetization is related to the internal field by the susceptibility of the material, χ, which is a measure of how much a material will become magnetized in an applied magnetic field, as:

$$\boldsymbol{\psi} = \chi \boldsymbol{h_{in}} \tag{3.20}$$

In this case it possible to assume an object made of material with a high nominal susceptibility being magnetized in relatively weak fields, such that χ » 1 (which is typical of many remote-manipulation and wireless-actuation tasks), so the magnetization is dominated by the geometry of the object and is insensitive to the nominal material susceptibility.

The magnetization curve of a general ferromagnetic material is depicted in Figure 3.2. In this case the hysteresis (i.e., the magnetization is a function of both the current and previous values of the field) is present, and there is an asymptotic approach to a saturation ψ_{sat} but also a characteristic slope of the curve near $\|\psi\| = 0$, which is considered the nominal susceptibility of the material. Moreover, when the field returns to zero, in general the magnetization does not also return to zero. So, if the material has previously been brought to saturation, then bringing the field to zero will cause the magnetization to be equal to the remanent magnetization ψ_r, and it takes a coercive field $\boldsymbol{h_c}$ to bring the magnetization back to zero. Materials with low coercivity are known as soft-magnetic materials, and those with high coercivity are known as hard-magnetic materials.

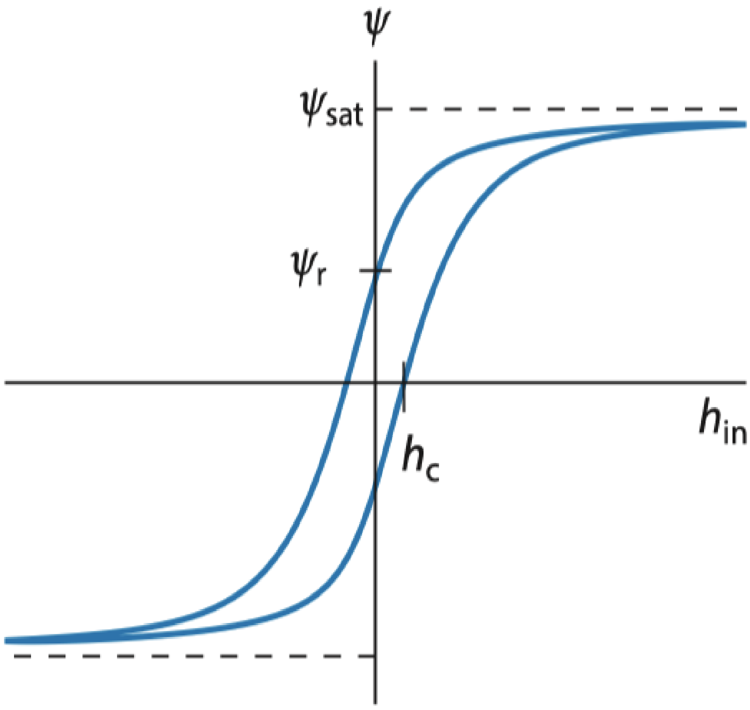


Figure 3.2: Magnetization of a general ferromagnetic material

Chapter 4

Actuation system

4.1 System setup

In order to perform a multi-stage magnetic actuation it is necessary a proper system and workspace too. First of all, the external source selected among the options described in the first chapter is the one composed by an external permanent magnet (EPM) with a cylindrical shape. The magnet is maneuvered by a robotic manipulator that is able to perform translations, rotations or rototranslations thanks to a MATLAB code that is linked to the manipulator by Simulink.
As written in the Chapter before, if the distance between two permanent magnets is much larger than the dimension of the objects, a dipole-dipole approximation can be considered. This approximation makes valid all the computations made in the Chapter 2.
Hence, the microscopic capsule to be actuated is composed by an internal permanent magnet (IPM). However, the magnet inside can have two different arrangements and therefore two different behaviours. So, a wireless link between the EPM and the IPM is established.
Moreover, the multi-stage actuation is made considering another smaller capsule in which it is possible to insert the particles to be actuated. This is a simplification of the real microrobotic system to be designed, where the nanoparticles are released by the capsule. However, in this way it is possible to appreciate better how the magnetic actuation is done.

4.2 Anthropomorphic manipulator

The robotic manipulator used is a Mitsubishi Industrial Robot 'RV-3SB':

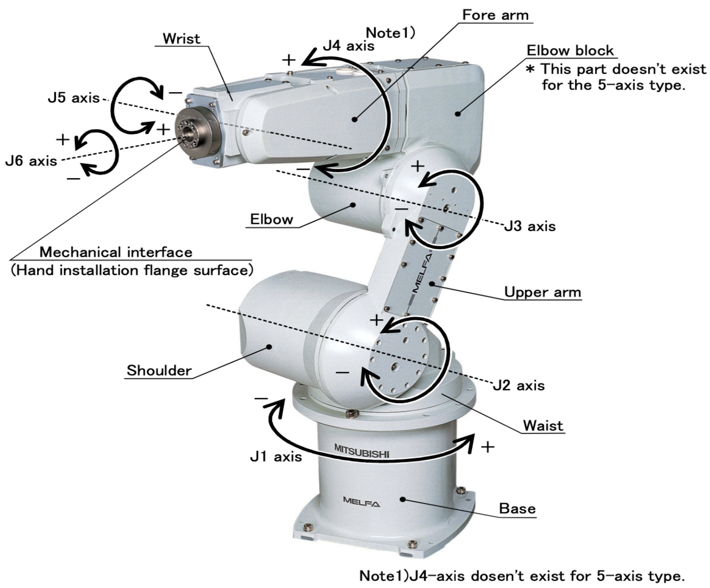


Figure 4.1: Mitsubishi Robotic Manipulator [12]

It is composed by 6 joints and it has 6 DoF. To be controlled, a controller and a teaching pendant are required.

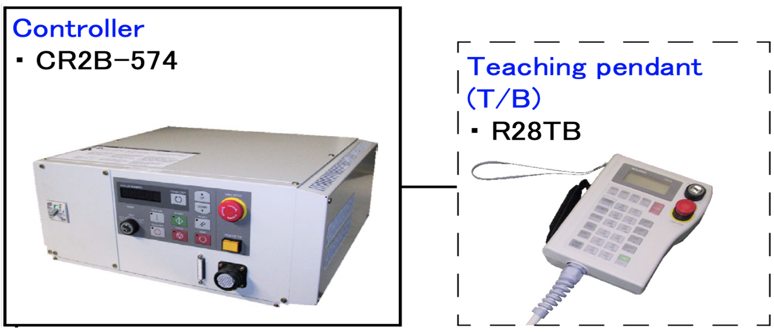
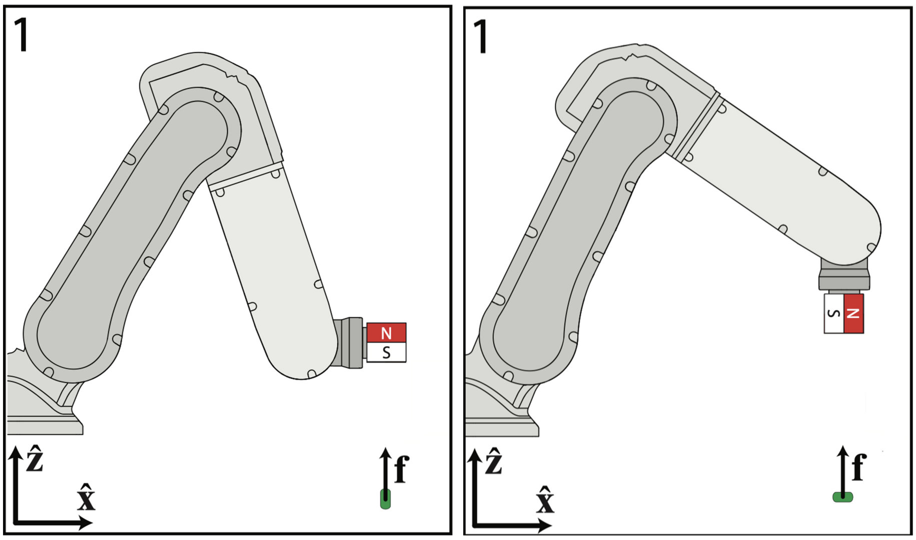


Figure 4.2: Controller [13]

The external permanent magnet used as a source is considered as an end-effector of the manipulator. The permanent magnet is 30cm long and 70cm high. Due to the 6 DoF of the manipulator it can be vertical or horizontal with respect to the support surface [9]:



(a) Horizontal Arrangement (b) Vertical Arrangement

The robotic manipulator is managed by a MATLAB function, so it possible to have different kind of movements on the magnet.

- Translation: the manipulator's joints n.x and y translate to with the magnet on the end effector that is always parallel with respect to the surface plane;
- Rotation: the joint n.6 of the manipulator rotate, and so the magnet too;
- Roto-translation: the two motions above are combined.

4.2.1 Simulink model

The MATLAB function *'Control'* described before is used inside a Simulink project that is able to establish a connection between the robotic arm and a joystick. This makes the control easier and strictly supervised. The Simulink project can be divided into 3 parts: input, output and logic.

4.2.2 Input

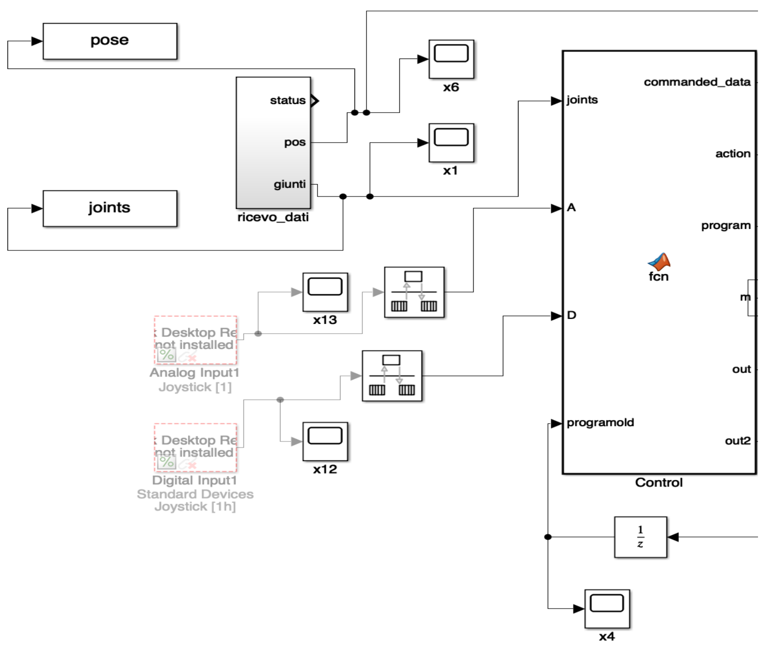


Figure 4.4: Input part

In this part of the project, the joystick is connected to the robotic manipulator through Digital and Analog input. However, in order to make the joystick's input adapted to be used by the MATLAB function, a Rate Transition block is needed. In fact, this block transfers data from the output of a block operating at one rate to the input of a block operating at a different rate.

Moreover, the joints and poses of the robotic manipulator are managed by an embedded MATLAB function called *'mitsubishi _CRn_ETH_data_unpack'* in which the TCP/IP packets are formed to be sent to the Mistubishi robotic arm with Ethernet Interface.

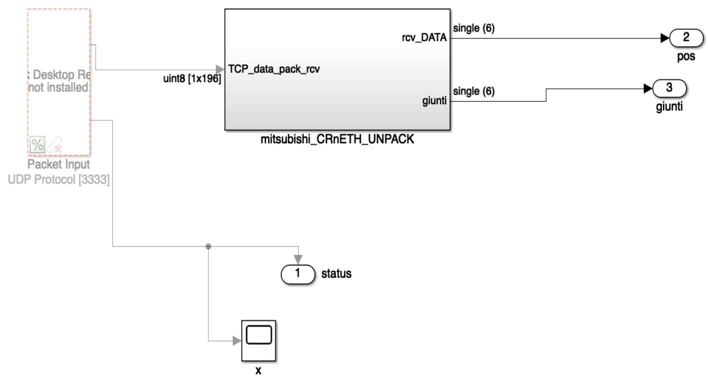


Figure 4.5: TCP/IP packets for Joint and Poses

4.2.3 Output

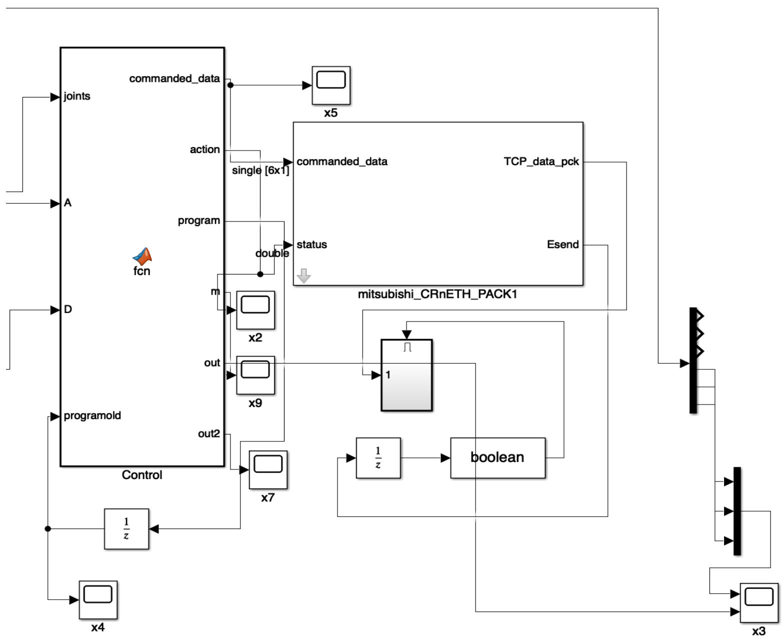


Figure 4.6: Output part

In the output part the MATLAB function, which processed the input data from the joystick, sent to the robotic manipulator the motion to be executed. These can be free movements or pre-set trajectories.

4.2.4 Logic

The logic part consists into the MATLAB function *'Control'* that is the central part of the Simulink project and responsible for the execution of the movements of the robotic arm. It is a link between the two parts described before. First of all, the Digital values from the input parts are converted into values and allocated into variables that can be named as the real buttons of the joystick (R1,R2,J1,J2 etc). The same is valid also for the Analog values. So that, if one of these buttons is pushed, an action is executed, that can be a cartesian translation or rotation or a trajectory. In particular, the main actuation commands used are the roto-translation and the rotation:

- Roto-translation: is made pushing at the same time the SELECT button, to activate the action n.5 and R1, so the joint n.3 and 5 of the robotic manipulator translate to the right while the joint n.6 (end-effector of the robot and so the permanent magnet) rotates clockwise. In the code this can be done in the following way:

```
if (action==5)
    commanded_data=joints;

    % -----don't move following joints
    %     q(program(1),1:5)=commanded_data(1:5,1);

    if (R1==1) % ------ translate and and rotate magnet
            %kine pane
            qp_off= joints ;
            S=directkinematic_mod(double(qp_off));
            S1=transl_pane(0,0.0003,0)*S;
            I=inversekinematic_mod(S1);
            if (joints(3)<0)      % elbow down
                if (joints(5)<0) % wrist down
                    qr=I(:,4) + offset_p;
                else              % wrist up
                    qr=I(:,3) + offset_p;
                end
            else                  % elbow up
                if (joints(5)<0) % wrist down
                    qr=I(:,2) + offset_p;
                else              % wrist up
                    qr=I(:,1) + offset_p;
                end
```

```
            end

        %      send step command
        commanded_data(1,1)=commanded_data(1,1)+single(JointStep(1));
        commanded_data(2,1)=commanded_data(2,1)+single(JointStep(2));
        commanded_data(3,1)=commanded_data(3,1)+single(JointStep(3));
        commanded_data(4,1)=commanded_data(4,1)+single(JointStep(4));
        commanded_data(5,1)=commanded_data(5,1)+single(JointStep(5));
        commanded_data(6,1)=commanded_data(6,1)+single(0.3*omega*vHz);

    end
```

The same is valid for the opposite direction.

- Rotation: Instead, a simple rotation of the joint n.6 is induced pushing at the same time the R2 button, to activate the action n.6, and R1 or L1 depending on which type of rotation is needed. This can be translated:

```
if (action==6)
    commanded_data=joints;

    JointStep=[sat, sat, sat, sat, sat,0.5*omega*vHz];

    segno=(1);

    if L1==1
        commanded_data(5,1)=commanded_data(5,1)+single(JointStep(5)*segno);
    end

    if R1==1
        commanded_data(6,1)=commanded_data(6,1)+single(JointStep(6)*segno);
    end
end
```

4.3 Magnetic capsules

As described in the chapters before, the micro-robotic capsules are actuated using an external magnetic field properly generated by an external permanent magnet (EPM). However, the magnetic property of the capsule is due to the presence of magnetic elements inside or outside it. Hence, inside the capsule it is possible to insert a very small permanent magnet to interact with the external one following the dipole-dipole approximation. Moreover, it is necessary to distinguish the capsules depending on how the internal magnet is located with respect to the longitudinal axis of the capsule. The internal permanent magnet (IPM) is a cylindrical magnet and it can be represented with a north (red) and a south (blu) face. Also, the capsule can have external powered coils wrapped around it. In this case the magnetic field produced is not very high, since the capsule analysed is millimetric, but it is possible to use it to have local actuation for the nanoparticles to be released.

4.3.1 Capsule with Axial Magnet

This capsule has an internal permanent magnet (IPM) with the longitudinal axis along the one of the capsule:

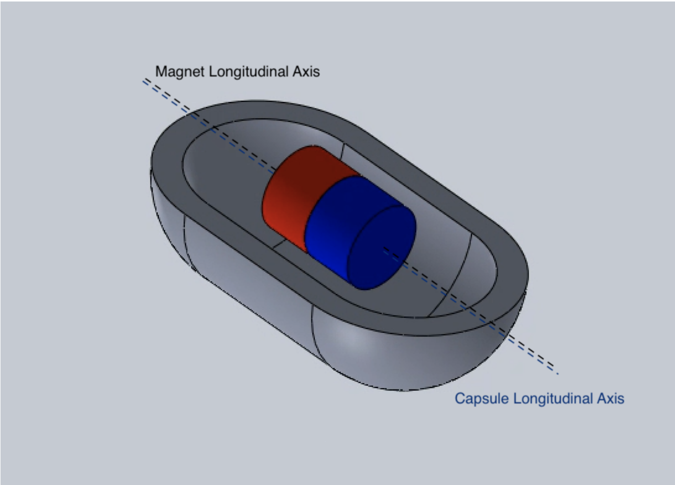


Figure 4.7: Axial Capsule

In particular, the Capsule Longitudinal axis is represented as a blue dotted line, while the one of the Magnet is represented in black. In this case the two lines are coincident.

4.3.2 Capsule with Transverse Magnet

This capsule has an internal permanent magnet (IPM) with the longitudinal axis perpendicular to the one of the capsule:

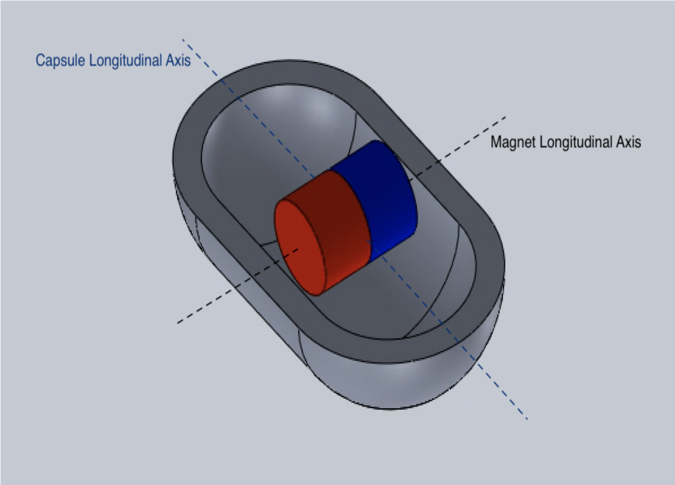


Figure 4.8: Transverse Capsule

Again, the Capsule Longitudinal axis is represented as a blue dotted line, while the one of the Magnet is represented in black.

4.3.3 Capsule with coil

In this case the coil wraps the entire capsule to have stronger computations to analyse:

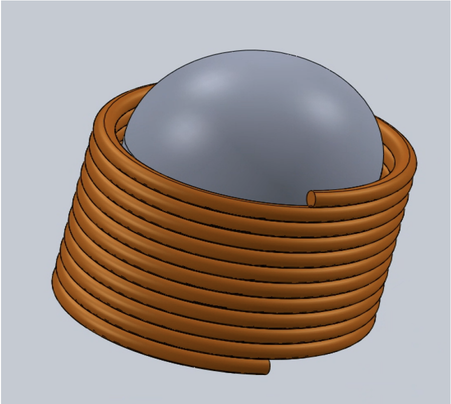


Figure 4.9: Coil Capsule

4.3.4 Capsule with Ferromagnetic Microparticles

Inside this section it is also possible to describe another type of capsule, that is the one with the nanoparticles inside it.
Actually, they should be inside the capsule with the magnet and released with a proper releasing mechanism. However, to better understand how they can move under the effect of a magnetic field, but also considering that the releasing mechanism is not part of this Thesis work, the microparticles are analysed as a part of a spherical capsule to be controlled through the external permanent magnet, but also and above all through the capsule with the internal permanent magnet. In fact, the aim is to have these particles around the mother-capsule, after their release, and so to use them for specific areas of the human body.
The particles used are a powder of Neodymium-Iron-Boron Ferromagnetic Microparticles (NdFeB). These type of magnets are permanent magnets, so they can be used to simulate in a stronger and more visible way the actuation to have. In particular, the powder application can have also some hazards, especially related to eye injuries due to their small size, but also respiratory since they can be easily inhaled.

Chapter 5

Actuation analysis

In this chapter a more detailed study of the actuation of the capsules is done. In particular, the study will be divided considering the different type of capsules: Capsule with Axial magnet, Capsule with Transverse Magnet, Capsule with Ferromagnetic powder.

The actuation can be distinguished into the one of the single capsule and the global one, that concerns the multi-stage motion. Moreover, it is possible to see also the motion of the Ferromagnetic powder due to the capsule with the coil wrapped around.

As described in the chapters before, the motion of the capsule will depend both on the permanent magnet inside it, but also on the arrangements of the External Permanent Magnet as end-effector of a robotic arm. So that, for each capsule two distinguished movements can be analysed depending on how the external source controls it. In particular, the two main movements that is possible to show are rolling and tumbling.

Moreover, it is important to know what type of External Permanent Magnet is used to actuate the capsules.

Actually, also the types of movement of the robotic arm (rotation or translation etc.) can influence the motion of the capsule, however, only the rotation or at least the rototranslation is considered in this work.

5.1 External Permanent Magnet

An appropriate analysis of the External Permanent Magnet (EPM), that is used to actuate the capsule, is needed since its shape is a key factor to understand what type of movement can be expected from the different capsules. The Permanent magnet used is a cylindrical magnet with length $l = 70cm$ and and diameter $d = 60cm$. In particular, the magnet is divided into two poles: north as red and south as green. However, the poles are divided along the longitudinal axis of the magnet, so the two halves are along the length of it.

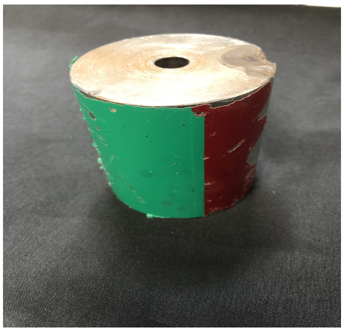


Figure 5.1: External Permanent Magnet

As described in the Chapter before, the magnet is considered as an end-effector of the Robotic Manipulator. It can be set in a Vertical or Horizontal position with respect to the surface plane. So, if the magnet is considered in a Vertical position and it is subjected to a rotational movement, a rotating magnetic field is produced that is able to induce a Rotation on the capsules to be actuated. On the contrary, if the Horizontal arrangement is considered, the rotational movement will produce a Rolling or Tumbling motion depending on the type of capsule analysed.

5.2 Rolling, Tumbling, Rotation

- Rolling: The rolling movement is a rotational movement of the capsule along its longitudinal axis. Considering the capsule laying on its side the rolling motion can be represented as:

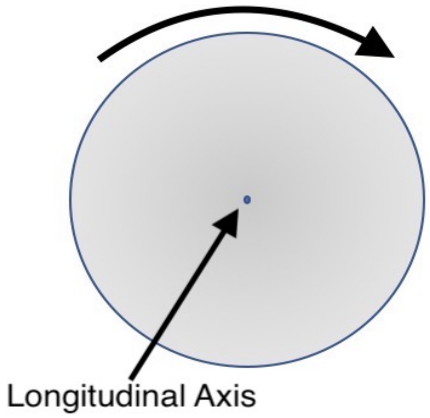


Figure 5.2: Rolling motion

- Tumbling: The tumbling movement is a rotational movement of the capsule along its transverse axis. Considering the capsule set vertically the tumbling motion can be represented as:

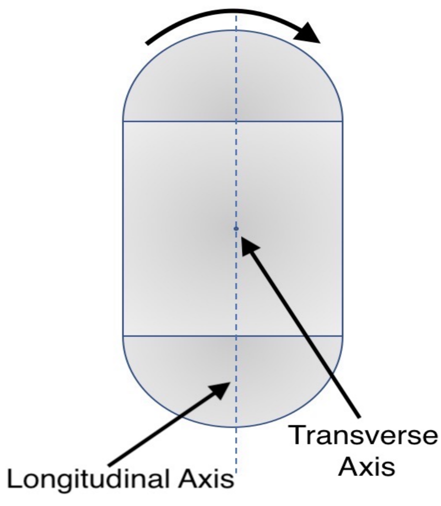


Figure 5.3: Tumbling motion

- Rotation: The rotating movement is a rotational movement of the capsule along its normal axis. Considering the capsule laying on its side the rotating motion can be represented as:

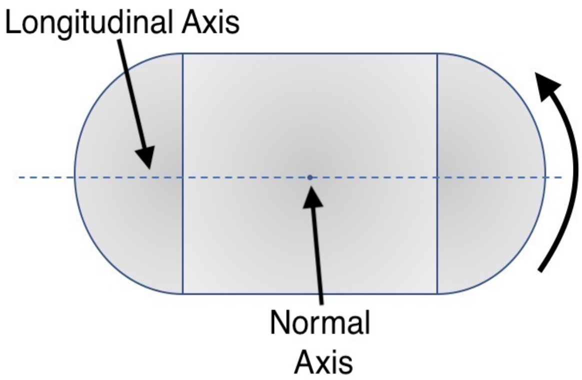
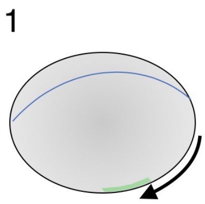


Figure 5.4: Rotating motion

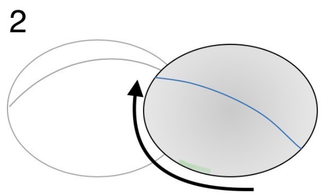
5.3 Capsule with Axial magnet motion

In Chapter 4 the Capsule with Axial magnet was described as the one with an internal permanent magnet (IPM) with the longitudinal axis along the one of the capsule. Now, it is possible to study its motion with the two arrangements of the External Permanent Magnet (Vertical or Horizontal) under a rotational movement. Moreover, considering the capsule as made by two halves joined together, it is possible to colour one of them with a green stain in order to simulate the motion expected.

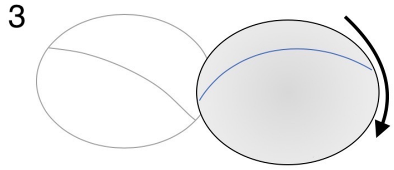
- Vertical EPM: Considering the Figure 4.3b the External Permanent Magnet is set vertically with respect to the support surface and it is subjected to a rotational movement. Since the capsule to be actuated is the one depicted in Figure 4.7 it can be expected a rotational movement of it since the magnetic fields of the two magnets are perpendicular to each other, so there will a magnetic torque, that responsible for the rotation, and a magnetic force due to the attraction of the magnets that is responsible for the rolling motion:



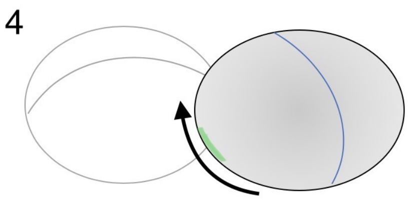
(a)



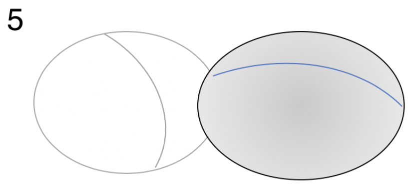
(b)



(c)



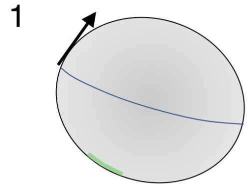
(d)



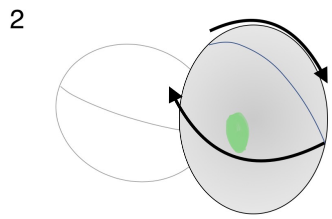
(e)

The capsule depicted in 5.5a starts its motion in a certain position with the green stain in the bottom half. When it is subjected to a rotating magnetic field the magnet inside starts to rotate too. So, the capsule changes its inclination in 5.5b and rotate until the green stain is in the upper half as in 5.5c. Again, if the EPM is still rotating the capsule rotates too as in Figures 5.5d and 5.5e.

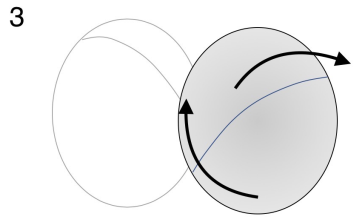
- Horizontal EPM: Considering the Figure 4.3a the External Permanent Magnet is set horizontally with respect to the support surface and it is subjected to a rotational movement. Since the capsule to be actuated is the one depicted in Figure 4.7 it can be expected a tumbling movement due to the magnetic attractive force and to the magnetic torque:



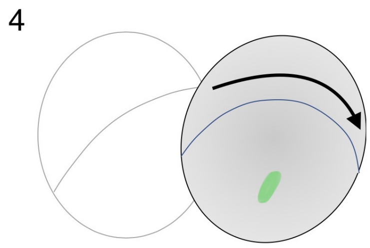
(a)



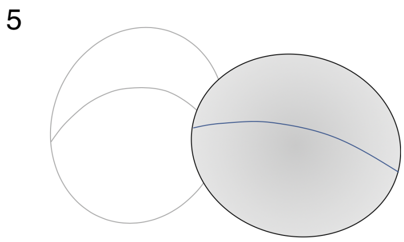
(b)



(c)



(d)



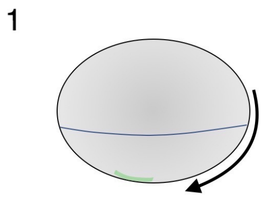
(e)

The capsule depicted in 5.6a starts its motion in a certain position with the green stain in the bottom half. When it is subjected to a rotating magnetic field the magnet inside starts to orient itself to the opposite pole of the EPM as in Figure 5.6b. So, the capsule starts to tumble and rotate, so the green stain will be in the back of the capsule as in Figure 5.6c. Again, if the EPM is still rotating the capsule rotates and tumbles too as in Figures 5.6d and 5.6e.

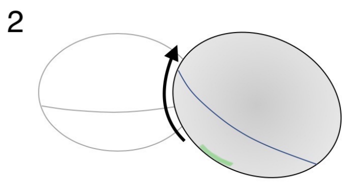
5.4 Capsule with Transverse magnet motion

This Capsule was described as the one with an internal permanent magnet (IPM) with the longitudinal axis perpendicular to the one of the capsule. It is possible to study its motion with the two arrangements of the External Permanent Magnet (Vertical or Horizontal) under a rotational movement. A green stain is used as before to distinguish the two halves.

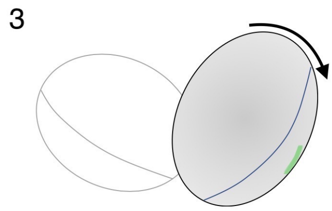
- Vertical EPM: Again, considering the Figure 4.3b the EPM is set vertically and it is subjected to a rotational movement. Now the capsule considered is the one in Figure 4.8, however it can be expected a motion similar to the Axial Capsule in the same condition. In fact, it can be expected a rotational movement due to a magnetic torque. Now, the magnetic attractive force is negligible due to the type of the capsule:



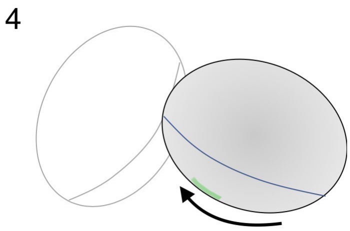
(a)



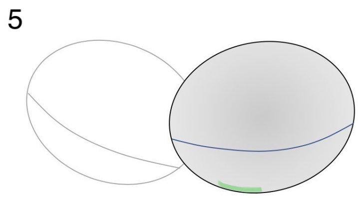
(b)



(c)



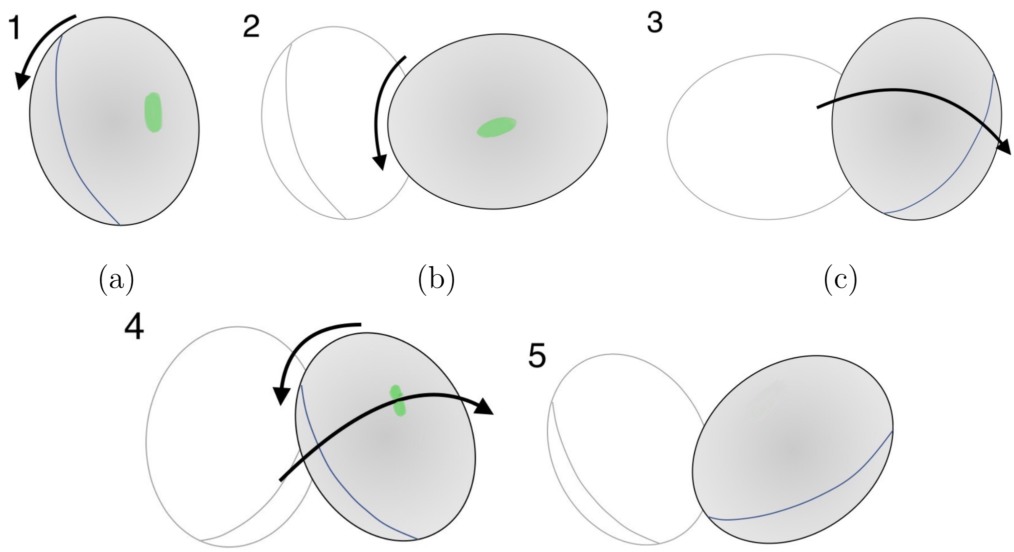
(d)



(e)

The capsule depicted in 5.7a starts its motion in a certain position with the green stain in the bottom half. When it is subjected to a rotating magnetic field the magnet inside starts to rotate too. However, the capsule motion is different compared to the one of the Axial Capsule in the same condition. In fact, the capsule rotates around its normal axis like in Figure 5.7b and Figure 5.7c. Again, if the EPM is still rotating the capsule rotates too as in Figures 5.7d and 5.7e.

- Horizontal EPM: Considering the Figure 4.3a the External Permanent Magnet is set horizontally with respect to the support surface and it is subjected to a rotational movement. Since the capsule to be actuated is the one depicted in Figure 4.8 it can be expected a rolling movement due to the magnetic torque generated by the rotating magnetic field, but also a rotation due to the magnetic attractive force between the poles of the magnets:



(a) (b) (c)

(d) (e)

The capsule depicted in 5.8a starts its motion in a certain position with the green stain in the upper half. When it is subjected to a rotating magnetic field the magnet inside starts to rotate as in Figure 5.8b. So, the capsule rotates, so the green stain will be in the bottom half of the capsule as in Figure 5.8c. Again, if the EPM is still rotating the capsule rotates and rolls too as in Figures 5.8d and 5.8e.

5.5 Capsule with Magnetic powder motion

As described in Chapter 4 the Ferromagnetic Microparticles, used to simulate a possible targeted drugs delivery, are contained in a spherical capsule, smaller than the ones described above. The goal is to actuate this capsule through the combined motion of the Eternal Permanent Magnet and the "mother-capsule" with the Internal Permanent Magnet. Hence, a multi-stage magnetic actuation is thus formed. However, the particles should be controlled outside the magnetic capsule in order to use them in a proper way. So it is possible to study how they can be actuated together with a magnetic field. In particular, paramagnetic particles tend to attract each other to form chain-like structures in a magnetic field. So, a paramagnetic particle chain in fluid actuated by a rotating magnetic field generates a local fluidic vortex [13].

Referring to VPNS as vortex-like paramagnetic nanoparticle swarm, the generation process of it depends on the merging of vortices induced by rotating particle chains, The paramagnetic particle chains are first dispersed in fluid, rotating about their own centers when a rotating magnetic field is applied. The vortex induces attracting interaction forces on other chains, so gradually the distances between the chains are reduced. When the distance of two rotating chains they began to rotate simultaneously in a local and global way. Therefore, after continual merging, one or more major vortices induced by multiple particle chains will be generated.

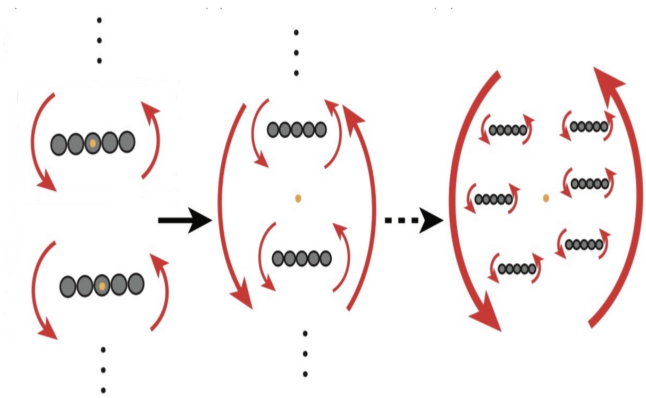


Figure 5.9: Vortex-like paramagnetic nanoparticles swarm

In order to simplify this actuation, that requires a in-depth study on fluid-dynamics that is not part of this Thesis work, the particles are considered inside a capsule to make them already gathered together.

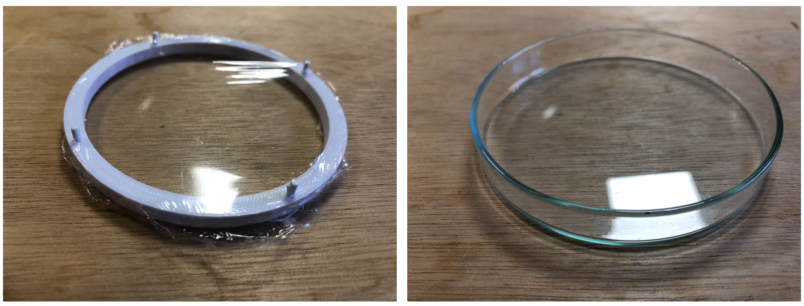
5.6 Global motion

The multi-stage magnetic actuation is analysed by combining all the contributes described above:

- Robotic Manipulator: The External Permanent Magnet considered as the end-effector of the manipulator can be Vertical or Horizontal with respect to the surface plane as in Figures 4.3a and 4.3b.

Figure 5.10: Robotic Manipulator

- Capsule with Internal Permanent Magnet: It is placed under the EPM in order to be actuated thanks to the external magnetic field properly generated. In particular, it is placed over a layer of foil properly stretched by a 3D printed support. This support is located in a petri that can be closed by another petri over it to reduce possible drags.



(a) Support with Layer of Foil (b) Petri

- Capsule with Ferromagnetic powder: The capsule is placed under the one with the IPM. They are separated by the layer of foil that is suitable have a full vision of the the system since it is both transparent and thin.

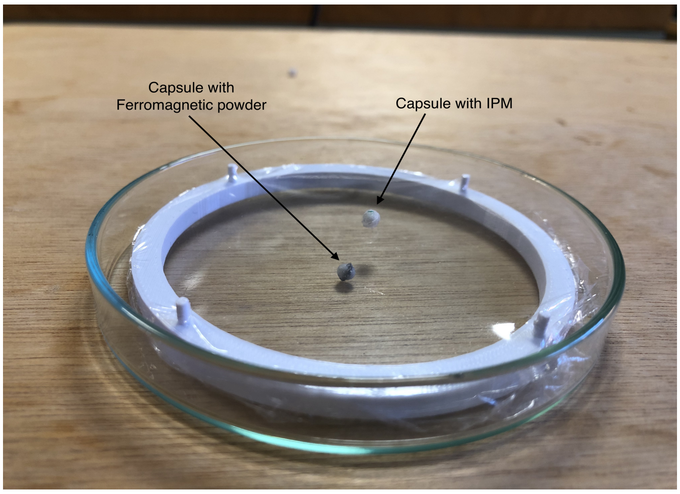


Figure 5.12: Capsules' Setup

So it is possible to show the entire system:

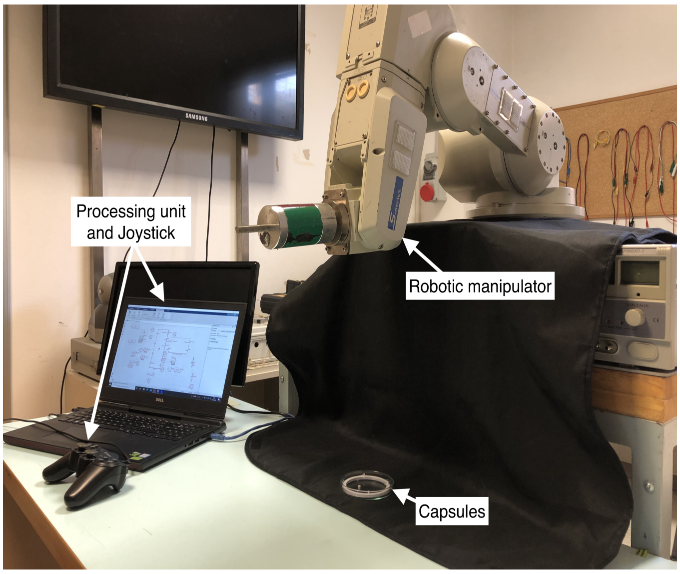
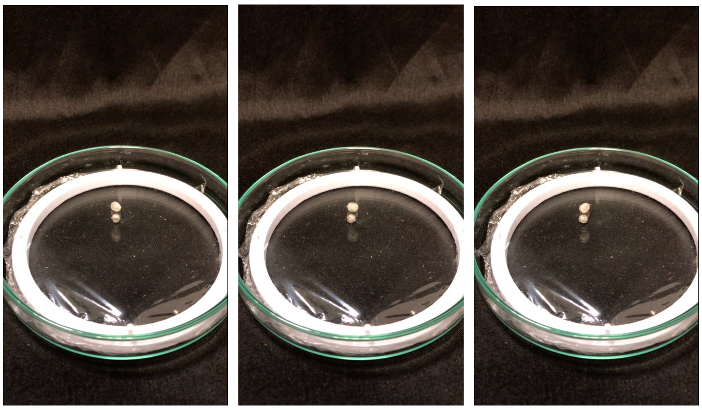


Figure 5.13: System Setup

Hence, the global actuation can be analysed. In particular the focus is set to the capsules motion considering a rotational movement of the EPM.

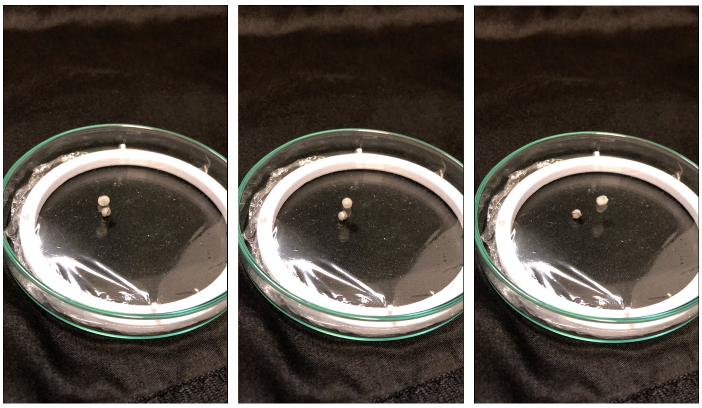
Capsule with Axial magnet

- Vertical EPM: As described before with a Vertical rotating EPM it is present a rotational movement of the capsule with the IPM due to a magnetic torque. The capsule containing the Ferromagnetic powder is expected to follow the rotation since it is affected by the same phenomenon. Moreover, the attraction between the two capsules is a key factor for this actuation.



(a) Start (b) Middle (c) End

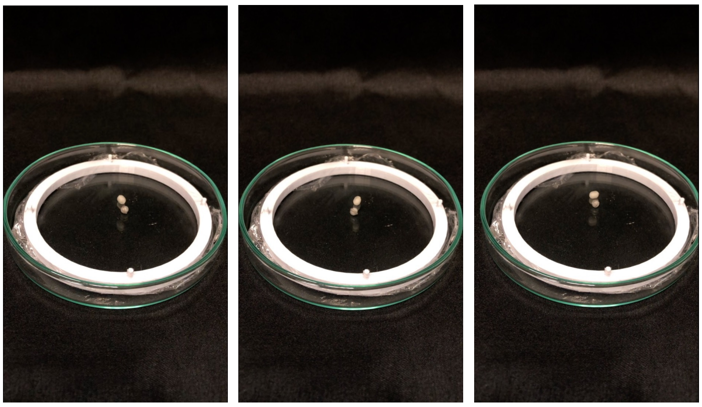
- Horizontal EPM: Now, with a Horizontal rotating EPM the capsule with the IPM is subjected to a tumbling motion, while the one with the powder is subjected to a rolling motion. This difference makes the interaction very difficult and the combined motion of them is expected to be not so good.



(a) Start (b) Middle (c) End

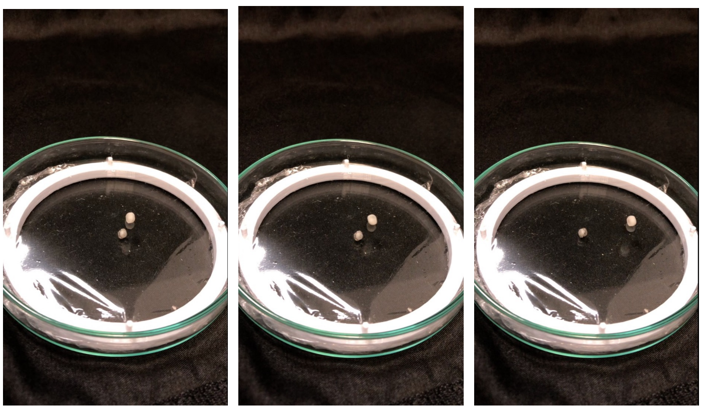
Capsule with Transverse magnet

- Vertical EPM: Considering again a Vertical rotating EPM, the capsule with the IPM has a similar behaviour of the other one described above. Moreover, the capsule containing the Ferromagnetic powder is expected to follow the rotation as well. However, the attraction between the two capsules is a lower than the previous case, so the motion is expected to be less consistent.



(a) Start (b) Middle (c) End

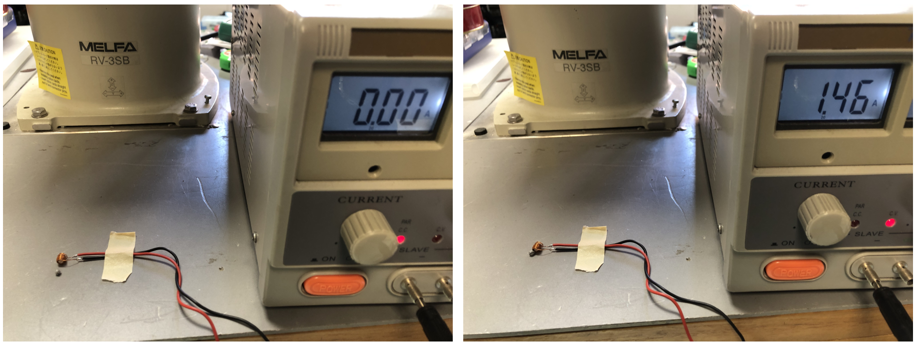
- Horizontal EPM: With a Horizontal rotating EPM the capsule with the IPM is subjected to a rolling motion. This can be seen also in capsule with the Ferromagnetic powder, however the interaction is still difficult since the poles of the two magnets can repel each others.



(a) Start (b) Middle (c) End

5.7 Capsule with coil motion

As described in the Chapter before, the magnetic field produced by a millimetric coil is be very low, so this type of capsule can be used to have local actuation near the capsule. In particular, it is possible to combine the IPM with the coil to actuate the magnetic capsule with the modalities explained above and to actuate the particles in a more precise way. It is known that the magnetic field depends both on the radius and number of the coil, but also on the current flowing through it. So it is expected to have a stronger magnetic field, and so a stronger interaction between the capsules, when the current is high and a lower magnetic field when the current is low:



(a) Low Current (b) High Current

It is possible to see that if the current is low the capsule with Ferromagnetic powder is not attracted by the coil since there is no magnetic field produced. On the contrary, when the current is flowing the capsule is attracted. However, the attraction can be seen only along the axis of the coil since the magnetic field is strong inside it (but also at a certain distance) and negligible on its side. So, if the current is constantly increased and decreased it is possible to have an oscillating motion of the particles. This can be used to have a more specific motion of them for targeted operations.

Chapter 6

Experimental results

In this chapter the performance of the proposed methodology is evaluated by means of computational simulations, in which all the magnetic quantities of the system (i.e. Magnetic Field, Magnetic Force and Magnetic Torque) are computed through Matlab. The aim of this Chapter is mainly to prove the effectiveness of the theoretical formulas to study possible implementations of simulated scenarios for safer study and experiments in the future. To do this all the theoretical computations are compared with the real values that are sensed through the Magnetic Field Sensor Infineon TLE493D for a decreasing value of distance of a capsule from the source. All the physical quantities of the elements of the system are measured accurately to consider the approximations made as close as possible to the real case. Moreover, to get a complete simulation of the actuation of a micro-robotic system, an inverse solution is explained to find the value of the distance of the magnetic element from the source in order to cover all the possible existing scenarios.

6.1 Magnetic Field Sensor

The Infineon TLE493D 3D magnetic sensor is an evaluation board equipped with a magnetic sensor for three dimensional measurement combined with an ARM® Cortex™-M0 CPU. Micro USB connector for power supply and communication with the Graphical User Interface (GUI). The board includes: a LED for indication of power supply and debugging; two LEDs for user configuration; Voltage regulator, reverse current protection diode and ESD protection diode; Pin headers to access data lines (e.g. via oscilloscope, external microcontroller). The HW consists of a 5 cm long / 1.5cm wide PCB which includes one XMC4200 (debugger), one XMC1100 (target device), pin headers, the target sensor + application circuit implementation placed on a breakable side of the PCB.The Firmware implements the basic sensor functions: software reset power up, mode of operation (master controlled, fast / low power / ultra low power), I2C acquisition (timer based / interrupt based), streaming all data to the PC, rolling counter check recover routine etc.

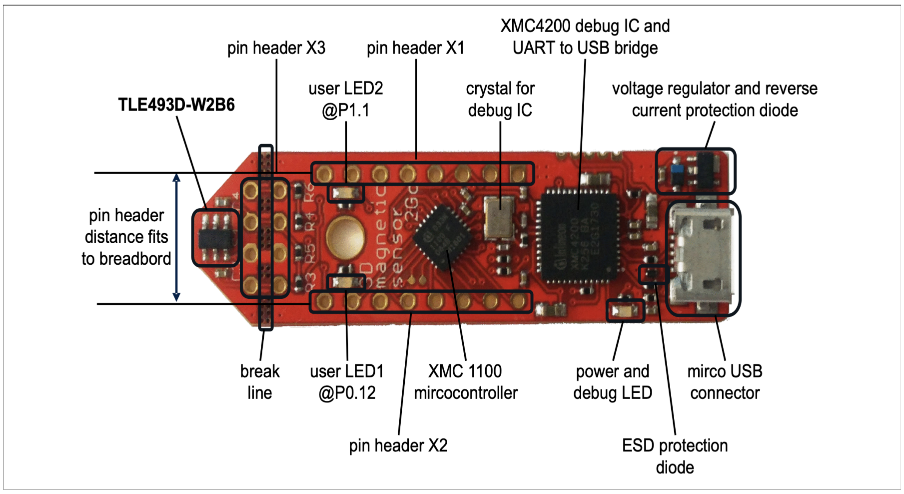


Figure 6.1: Magnetic Sensor

The 3D Magnetic Sensor is supplied via the USB cable. It is also possible to provide an external power supply. If this is the case, a few considerations must be taken into account as described below. It must be supplied by external 5 Volt DC power supply connected to the micro USB plug. The voltage regulator shifts the voltage level to 3.3 V for the microcontrollers and the 3D magnetic sensor. The Power & Debug LED indicates that the presence of the generated 3.3 V supply voltage. [14]

6.2 MATLAB computations

As described before, the physical quantities of the elements of the system are measured accurately to consider the approximations made as close as possible to the real case. In the table below the properties of External Permanent Magnet, Capsule and Ferromagnetic particles are exposed:

	E.P.M.	**Capsule - I.P.M.**	**Capsule - Particles**	**Particles**
Length	70 cm	4.26 mm	3 mm	/
Radius	30 cm	3.24 mm	3 mm	250μm
Remanence	Br=1.19T	Br=1.19T	Msp=800kT	Msp=800kT
Shape	Cylindrical	Cylindrical	Spherical	Powder

Table 6.1: Magnetic elements' properties

The properties are used through a Matlab script where the theoretical formulas described in Chapter 3 are implemented. In particular, considering the Magnetic Field equation 3.1, the magnetic moment is a key factor that depends on the Volume of the magnet analysed, and so on its shape. As described in the State of the Art Chapter the two ways to compute the magnetic moment are represented in the equations 2.2 and 2.3. Moreover, the Magnetic quantities are evaluated for the three axis x, y and z. To do this, the distance from the source is set with three contributes as a symbolic function in order to better analyse the field equations. So, applying the partial derivative of the magnetic field over three axis it is possible to obtain the gradient field. The gradient and the magnetic field are used to obtain respectively the magnetic force and torque induced by the source on the capsule. However, it is necessary to know the magnetic moment of the capsule that is the one in the equations 3.9 and 3.14. These considerations can also be made for the capsule with the coil wrapped around it and for the one with the Ferromagnetic powder. In particular, the coil's computations are useful to know the order of magnitude of the magnetic field for the local actuation of the particles released. To check the validity of the computations two plots representing the magnetic field's trend with respect to the distance are made since there can be two different arrangements of the EPM as explained before. The distance is considered as increasing, so it is expected an hyperbolic behaviour of the magnetic field with an asymptote on the distance axis.

- Horizontal EPM: The trend of the Magnetic Field generated by the External Permanent Magnet in a Horizontal position:

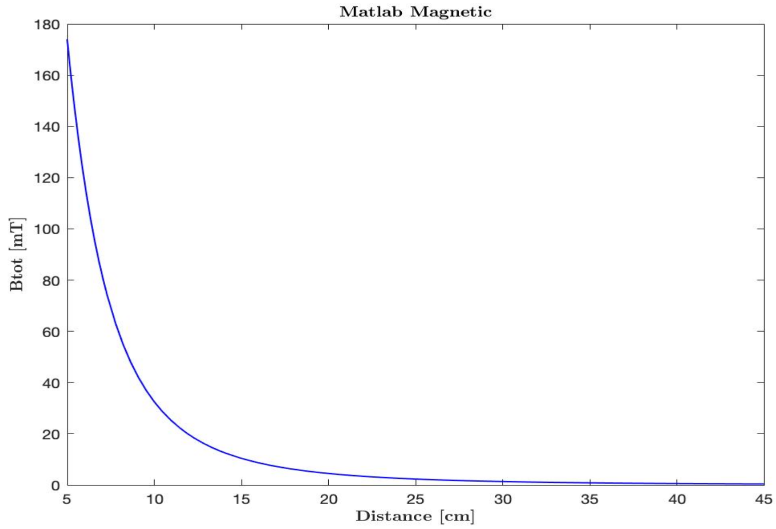


Figure 6.2: Matlab Magnetic Field trend - Horizontal EPM

- Vertical EPM: The trend of the Magnetic Field generated by the External Permanent Magnet in a Vertical position:

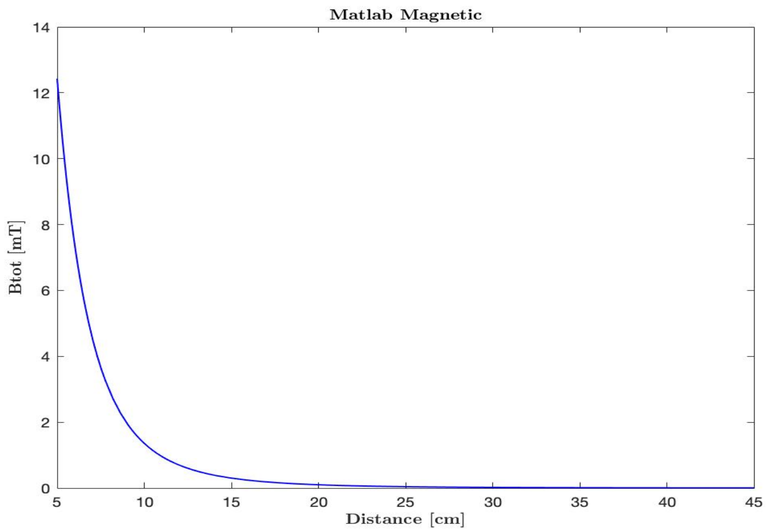


Figure 6.3: Matlab Magnetic Field trend - Vertical EPM

The two plots represent very well the expected trend of the Magnetic Field, since it decreases as the distance increases since it is inversely proportional to it.

In particular, considering the small physical dimensions of the EPM, the magnetic field sensed that is placed on the y axis is very low and it is measured in mT. Moreover, it is evaluated for the three axis and then the total value is obtained as:

$$B_{tot} = \sqrt{b_x^2 + b_y^2 + b_z^2} \tag{6.1}$$

On the other case, on the x axis the distance between the EPM and the point where the field is sensed is set in cm. However, it is considered only the contribute on the z axis since the point is considered as under the center of the EPM (both in the Vertical and Horizontal arrangement).

The complete script used for the computations is attached in Appendix A.

6.3 Experimental computations

Contrary to the Matlab computations, the Experimental ones take into account the real magnetic objects in a real workspace. So, it is expected to have some differences with respect to the other case, since all the drags and misalignments are not considered in the Matlab scenario.

As described previously, to do all the measurements, that are needed to plot the trend of the Magnetic Field magnitude with respect to the distance, a Magnetic Field sensor Infineon TLE493D is used.

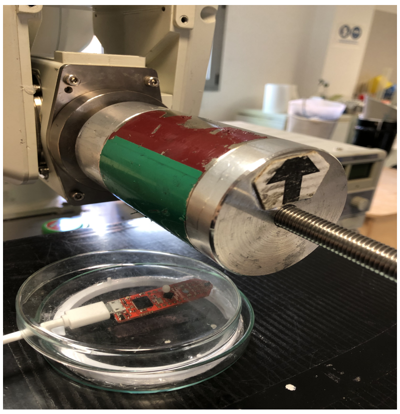


Figure 6.4: Sensor Measurements

- Horizontal EPM: The trend of the Magnetic Field generated by the External Permanent Magnet in a Horizontal position:

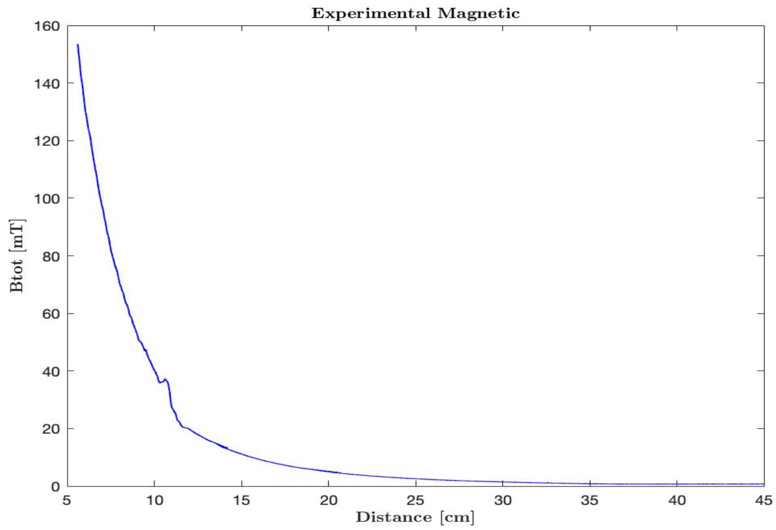


Figure 6.5: Experimental Magnetic Field trend - Horizontal EPM

- Vertical EPM: The trend of the Magnetic Field generated by the External Permanent Magnet in a Vertical position:

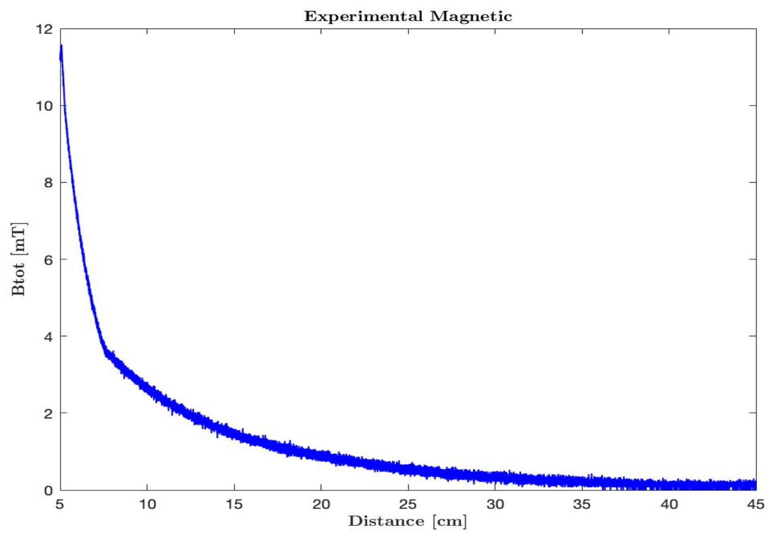


Figure 6.6: Experimental Magnetic Field trend - Vertical EPM

Also in this case the two plots represent well the expected trend of the Magnetic Field, since it decreases as the distance increases since it is inversely proportional to it. However, it is also possible to highlight that the behaviour is not as smooth as the one shown in Matlab, since it considers also small but significant variations in the measurement procedure. Moreover, the Magnetic Field sensor cannot be very precise when the distance is very big due to the intensity of the field but also to the dimension of the sensor itself.

In particular, it is possible to highlight that the plot representing the Field of the Horizontal magnet has a strange behaviour with a distance $\approx$ $10cm$, maybe due to a misalignment of the sensor during the measurement procedure. Furthermore, In the plot with the Vertical magnet the values oscillate from a minimum to a maximum. This is due to the fact that the EPM is mounted on a stand to be used as an end effector of the Robotic Manipulator. So there can be a shielding action which does not allow to have precise measurements.

6.4 Comparison

Now, it is possible to compare the plots of the two measurement methods.

- Horizontal EPM:

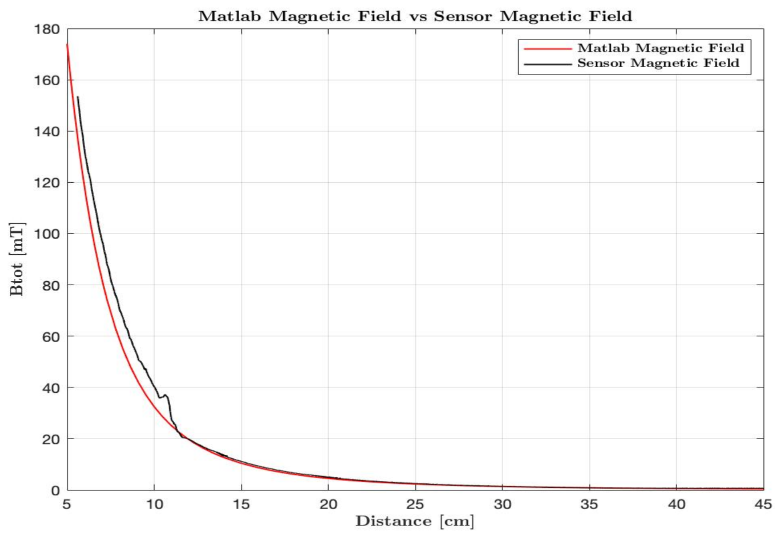


Figure 6.7: Comparison between Magnetic Field trends - Horizontal EPM

Considering the Horizontal EPM case, it is possible to see that the two trends, one corresponding to the Matlab computations in red and the other corresponding to the Experimental ones in black, are very similar. The two graphs overlap in most points with almost equal values along the curves. It can be seen very small differences for small distances, probably due to non perfect measurement procedure in the experimental case, but also to drags and different workspace conditions that the Matlab script does not take into account. Moreover, a non-linear area of the curve can be highlighted at $\approx 10cm$ of distance that can be traced to a misalignment of the sensor during the measurement procedure.

- Vertical EPM: Considering the Vertical EPM case, it is possible to see

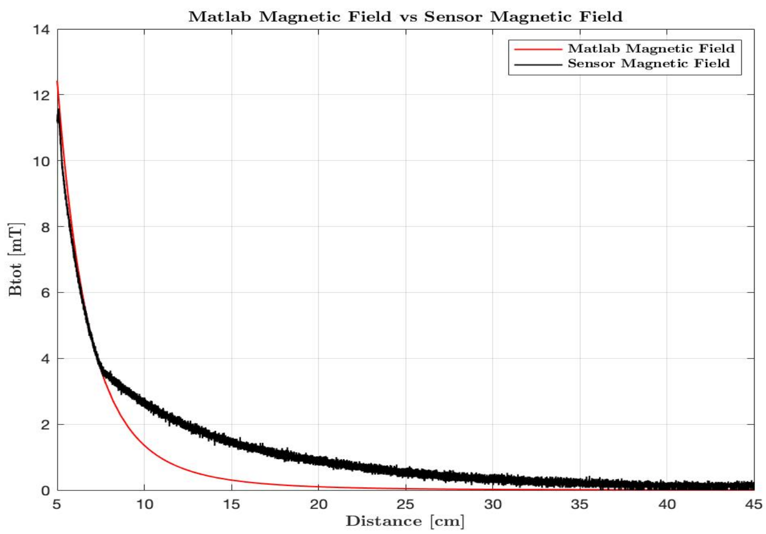


Figure 6.8: Comparison between Magnetic Field trends - Vertical EPM

that the two trends overlap for small distances. However, the two graphs start to be different at $\approx 7cm$. In fact, the sensor graph is higher than the other with higher values of magnetic field with the same distance. This is due to the fact that the EPM, as explained before, it is mounted on a stand. So there can be a shielding action which does not allow to have precise measurements. However, the two graphs overlap again for high distances.

6.5 Inverse solution

The inverse solution is set to find the value of the distance of a magnetic element from the source. To do it, it is necessary to know the value of the magnetic field that is inversely proportional to the distance.

So, it is possible to set the sensor at a distance equal to $d = 9.5cm$:

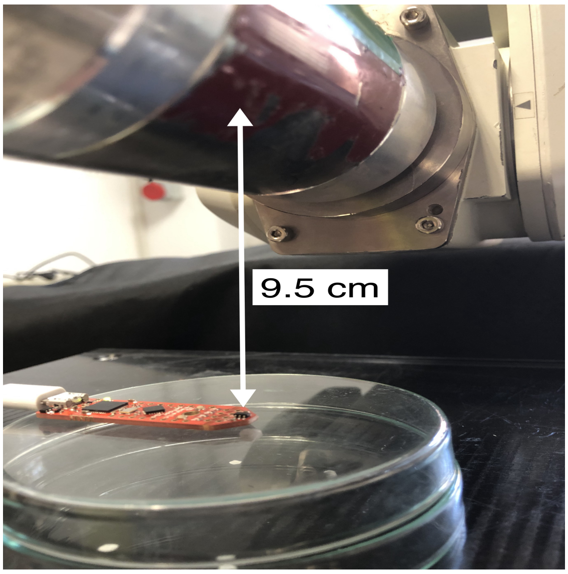


Figure 6.9: Sensor and EPM distance

The Magnetic Field contributes on the three axis are:

$$\begin{cases} b_x = 2.6mT \\ b_y = -3.9mT \\ b_z = 44.2mT \end{cases}$$

Implementing this values into a Matlab script which is able to solve the Magnetic Field equations for the three axis as in 3.3 it is possible to obtain the distance for each contribute:

```
eq1 = b(1) == 2.6*10^-3;
eq2 = b(2) == -3.9*10^-3;
eq3 = b(3) == 44.2*10^-3;
sol = vpasolve([eq1, eq2, eq3],[x,y,z]);

xSol = round(sol.x,5);
ySol = round(sol.y,5);
zSol = round(sol.z,5);

abs(xSol)
abs(ySol)
abs(zSol)
```

The values computed by the Matlab code are:

```
xSol = 0.00368
ySol = 0.00553
zSol = 0.09419
```

Since the sensor is placed under the EPM, the important value is $'zSol'$. Considering that the computations are made in $meters$, the obtained value is $9.419cm$. So, it is possible to compute the Relative and the Percentual Errors as:

$$E_r = \frac{TheoreticalValue - RealValue}{TheoreticalValue} = \frac{9.5 - 9.419}{9.5} = 0{,}00853 \tag{6.2}$$

$$E_p = E_r \times 100\% = 0{,}853\% \tag{6.3}$$

The error is very low considering a small distance, so this method seems to be suitable for simulated scenarios which can help to have safer experiments in future applications.

The complete script proposed above is attached in Appendix B.

Chapter 7

Conclusions

The proposed magnetic actuation model has shown interesting and encouraging results in terms of both target accomplishment and scenario simulation. The novel approach, which exploits the multi-stage magnetic actuation to control magnetic capsules with an induced movement between them as well as with the external source, allows to consider the microrobotic surgery as a new modality for targeted treatment. This version of capsule, even if it is smaller than the others used in the recent researches about their usage on in-vivo and in-vitro applications, manages to move efficiently through an external magnetic field. Furthermore, the different modalities of actuation, considering all the possible configurations of the IPM and EPM, allow to cover several workspaces. It is worth remarking that the proposed actuation method is anyway limited to a rotational movement which is able to induce a better motion to the Ferromagnetic particles and so to establish a multi-stage actuation that is the aim of this work. Moreover, it is worth remarking that the proposed work does not aim at developing a path planning model, rather the motion directions can be interpreted as a first step to explore how to manage in the best possible way a microrobotic capsule for targeted treatments. The usage of Matlab scripts, which implement theoretical studies about electromagnetism, enables faster study process and safer experiments.

Although the completeness of the proposed approach and the satisfactory results that have been achieved, it is anyway possible to outline a series of improvements and extensions which can be applied to this work:

- Despite the proved reliability and effectiveness of the proposed capsule, taking into account also its small dimension, it can be really improved but also better designed considering specific materials to meet the biocompatibility criteria, different methods of assembly and production.

- The capsule proposed is magnetized through an Internal Permanent Magnet, however the modality used to do it is very rough, so it could be interesting to study new ways to use permanent magnet inside the capsule that must be considered together with the production. Moreover, the coil outside the capsule used to have local actuation for the particles after their release can be improved considering a pre-installation on the surface of the capsule itself.

- The particles interaction with the capsule was made through a smaller one to simulate the control after their release. However, this is one of the crucial point of a research about targeted treatments. So, it can be done an in-depth study of a release mechanism of the particles from the magnetic capsule to the outside.

- Specific workspaces can be made to simulate the microrobotic surgery inside the human body, so it can be possible to use artificial veins or organs to better understand the best actuation methods in a realistic scenario.

Appendix A

Permanent Magnet Matlab Function

```
%%EPM's information
mu0 = 4*pi*10^-7;
k = mu0/(4*pi);
r = 30;
h = 70;
V = pi * r^2 * h;
Br = 1.19;
g = 9.81;

%%Axis
syms x y z real

I = eye(3,3);

dd = [x y z]'
ddn = norm(dd)
ddhat = (dd/ddn)

%%Computation of the dipole moment
m_em = Br * V/mu0;
m_emmtx = [0, 0, m_em]';

%%Computation of the magnetic field
bp = k * (1/ddn^3) * (3*(ddhat * ddhat') - I)
b = bp * m_emmtx
db = mygradient(b,[x,y,z])'
```

```
%%Computation of the force and torque induced by the EPM
f = db * m_capsmtx

fg = Vc*rhoc*g

t = skew_mcaps*b
```

Appendix B

Inverse Solution Matlab Function

```
clear all
%%EPM's information
mu0 = 4*pi*10^-7;
k = mu0/(4*pi);
r = 0.03;
h = 0.07;
V = pi * r.^2 .* h;
Br = 1.19;

%%Axis
syms x y z positive

I = eye(3,3);

dd = [x y z]';
ddn = norm(dd);
ddhat = (dd/ddn);

%%Computation of the dipole moment
m_em = Br * V/mu0;
m_emmtx = [0, 0, m_em]';

%%Computation of the magnetic field
bp = k * (1/ddn^3) * (3*(ddhat * ddhat') - I);
b = bp * m_emmtx;
```

```
%%Solution
eq1 = b(1) == 2.6*10^-3;
eq2 = b(2) == -3.9*10^-3;
eq3 = b(3) == 44.2*10^-3;
sol = vpasolve([eq1, eq2, eq3],[x,y,z]);

xSol = round(sol.x,5);
ySol = round(sol.y,5);
zSol = round(sol.z,5);

abs(xSol)
abs(ySol)
abs(zSol)
```

Bibliography

[1] Armando Ramos-Sebastian, Sung Hoon Kim, *Magnetic Force Propelled 3D Locomotion Control for Magnetic Microrobots via Simple Modified Three-Axis Helmholtz Coil System*, September 2021.

[2] Michael P. Kummer, Jake J. Abbott, Bradley E. Kratochvil, Ruedi Borer, Ali Sengul, and Bradley J. Nelson, *OctoMag: An Electromagnetic System for 5-DOF Wireless Micromanipulation*, May 2010.

[3] Federico Ongaro, Stefano Pane, Stefano Scheggi, Sarthak Misra, *Design of an Electromagnetic Setup for Independent Three-Dimensional Control of Pairs of Identical and Nonidentical Microrobots*, February 2019.

[4] Federico Ongaro, Claudio Pacchierotti, ChangKyu Yoon, Domenico Prattichizzo, David H. Gracias, and Sarthak Misra, *Evaluation of an Electromagnetic System with Haptic Feedback for Control of Untethered, Soft Grippers Affected by Disturbances*, June 2016.

[5] Eric Diller, Joshua Giltinan, Guo Zhan Lum, Zhou Ye and Metin Sitti, *Six-degree-of-freedom magnetic actuation for wireless microrobotics*, 2015.

[6] Jurgen Rahmer, Christian Stehning, Bernhard Gleich, *Remote magnetic actuation using a clinical scale system*, March 2018.

[7] Fuzhou Niu, Junyang Li, Weicheng Ma, Jie Yang, and Dong Sun, *Development of an Enhanced Electromagnetic Actuation System With Enlarged Workspace*, October 2017.

[8] Laliphat Manamanchaiyaporn, Xiuzhen Tang, Yuanyi Zheng, Xiaohui Yan, *Molecular Transport of a Magnetic Nanoparticle Swarm Towards Thrombolytic Therapy*, March 2021.

[9] Arthur W. Mahoney and Jake J. Abbott, *Five-degree-of-freedom manipulation of an untethered magnetic device in fluid using a single permanent magnet with application in stomach capsule endoscopy*, 2015.

[10] DEPARTMENT OF HEALTH AND HUMAN SERVICES Centers for Disease Control and Prevention. National Institute for Occupational Safety and Health, *Approaches to Safe Nanotechnology: Managing the Health and Safety Concerns Associated with Engineered Nanomaterials*, March 2009.

[11] Jake J. Abbott, Eric Diller, and Andrew J. Petruska *Magnetic Methods in Robotics*, 2019.

[12] Mitsubishi, *RV-3SB/3SJB Series - Standard Specifications Manual.*

[13] Jiangfan Yu, Lidong Yang and Li Zhang, *Pattern generation and motion control of a vortex-like paramagnetic nanoparticle swarm*, 2018.

[14] TLE493D-W2B6 MS2GO 3D Magnetic Sensor 2 Go evaluation kit, User Manual.