Hybrid electromagnet model for multiple mobile coil magnetic manipulation

Baptiste Véron, Arnaud Hubert, Joël Abadie and Nicolas Andreff
FEMTO-ST Institute - UMR CNRS 6174
AS2M department (Automatic control and Micro-Mechatronic Systems)
24 rue Alain Savary, 25000 Besancon (FRANCE).
Email: firstname.name@femto-st.fr

***Abstract*—In gastroenterology, endoscopic capsules have demonstrated their usefulness for diagnosis in the small bowel. However, they also show limitations due to the impossibility to control their progress in the small bowel. Magnetic actuation is often considered to control these capsules, but current systems are very bulky and some have stability concerns. To improve the manipulability of the capsule and to reduce the size of the magnetic system, it is interesting to consider a system composed of mobile electromagnets having a ferromagnetic core. These electromagnets allow to create large efforts at lower currents, but produce a magnetic field highly non-linear. This paper proposes a hybrid model (analytical adjusted on measures) to compute the magnetic field created by the electromagnets, and discusses the usefulness of this model.**

I. INTRODUCTION

There exist several paths towards small bowel exploration. The double-balloon enteroscopy allows the visualization of some parts of the small bowel (up to the beginning of the ileum) in real time, but not the whole small bowel. The capsule endoscope is a swallowable capsule embedding a camera which allows to take pictures all along the gastrointestinal tract, but has the major drawback of only moving thanks to peristalsis.

To cope with this lack of means for small bowel diagnosis several studies tried to enhance the capabilities of the capsule endoscopes, especially to actuate the capsule and allow the control of its position. Magnetic steering is quite appropriate for that, because magnetism is a contactless effect for which body tissues are transparent. Some studies have already been led on that topic using external permanent magnets (EPM) moving around the patient to steer the capsule embedding a small permanent magnet [1]. With the same objective, the Niobe II system from Stereotaxis has also been used [2]. These approaches showed critical limitations. The impossibility of turning off the magnetic field leads to a lack of stability, and the use of an industrial robot to move the EPM, can be dangerous for the patient and the medical staff. Other studies have led to the use of static electromagnets placed around the patient similarly to an MRI system [3]. These systems are extremely bulky, they do not let the staff access to the patient, and they use a large amount of energy.

Thus, these two approches can be combined to study a light weight system composed of several mobile electromagnets. This kind of system presents many advantages, as shown in [4]. It allows full dexterity with a shorter distance between the electromagnet and the manipulated object, what reduces the heat and the energy consumption. More, it allows to easily design redundant systems to enhance the manipulability of the magnetic object and the stability. Furthermore, the bulkiness of such a system is even more reduced by the use of electromagnets composed of a winding and a ferromagnetic core. These electromagnets permit to get large effort at lower currents, but the magnetic field created is highly non-linear, what makes its precise real-time computation difficult. To overcome this, an analytical model is proposed, and its usability is discussed.

II. ELECTROMAGNETIC MODELING

The magnetic efforts are computed via the magnetic field $\boldsymbol{B}$ produced by a magnetic source :

$$\begin{aligned} \boldsymbol{F_m} &= V \cdot \boldsymbol{\nabla} \left(\boldsymbol{M} \cdot \boldsymbol{B}(\boldsymbol{P}) \right) \\ \boldsymbol{C_m} &= V \cdot \boldsymbol{M} \wedge \boldsymbol{B}(\boldsymbol{P}) \end{aligned}$$

where V is the volume of the permanent magnet, $\boldsymbol{\nabla}$ is the gradient operator and $\wedge$ is the cross-product.

For electromagnets, three methods are commonly used to compute this magnetic field. The first method is to measure and to map the magnetic field over the whole workspace. The accuracy of this method relies on the precision and the number of measures. Its implementation is long and requires a large amount of memory to store the measures.

The second method, usually used for the design, consists in finite element modeling. This method is based on a mesh of the space, thus, it requires long computation time and a large amount of memory to store the data.

The third method is to use the well known dipole approximation :

$$\boldsymbol{B} = \frac{\mu_0}{4} \frac{I \ a^2}{r^3} \begin{pmatrix} 2\cos\theta \\ \sin\theta \\ 0 \end{pmatrix} \tag{1}$$

where μ_0 is the magnetic permeability of free space, a is the radius of a loop, I the current flowing in this turn, and (r, θ, φ) are the spherical coordinates where $\boldsymbol{B}$ is computed.

This analytical formula is only valid on some parts of the space around the electromagnet (for $r \gg a$) and does not take the ferromagnetic core into account. This greatly limits its use.

None of the existing models for computing $\boldsymbol{B}$ (mapping, finite elements, dipole approximation) satisfy the contradictory requirements of accuracy and real-time computation.

Actually, $\boldsymbol{B}$ is the curl of the vector potential $\boldsymbol{A}$: $\boldsymbol{B} = \boldsymbol{\nabla} \wedge \boldsymbol{A}$. In spherical coordinates, $\boldsymbol{A} = (A_r\ A_\theta\ A_\varphi)^T$ of one current loop has only one component :

$$A_\varphi = \frac{\mu_0}{4\pi} \frac{4Ia}{\sqrt{a^2 + r^2 + 2ar\sin\theta}} \left(\frac{(2-k^2)K(k) - 2E(k)}{k^2} \right) \tag{2}$$

where $K(k)$ and $E(k)$ are respectively the complete elliptic integrals of first and second order, for which k is defined as :

$$k^2 = \frac{4ar\sin\theta}{a^2 + r^2 + 2ar\sin\theta}$$

This allows to compute the magnetic field created by the winding by summing the contribution of each turn. To be taken into account, the ferromagnetic core is considered as a magnetic dipole located at the center of the coil, its magnetization depending on the current flowing in the coil. Thus, we propose to model the field generated by the coil and the core as a linear combination of (2) and the dipole approximation (1) :

$$\boldsymbol{B} = G_1 \cdot \sum_{a_{min}}^{a_{max}} \sum_{-L/2}^{L/2} \boldsymbol{\nabla} \wedge \boldsymbol{A} + G_2 \cdot \frac{\mu_0}{4} \frac{I\ a^2}{r^3} \begin{pmatrix} 2\cos\theta \\ \sin\theta \\ 0 \end{pmatrix} \tag{3}$$

where G_1 and G_2 are introduced to adjust the relative contribution of the winding and the core. These gains depend on parameters such as the core material, its temperature, etc.

The gains are identified by magnetic measures and robust linear regression, what makes (3) a hybrid model. TABLE I shows the relevance of this model compared to the others. Because it is analytical, it does not require memory for data storage, and it alows real-time computation. More, has a good accuracy, and it is setted up quickly, with few measures to identify the gains.

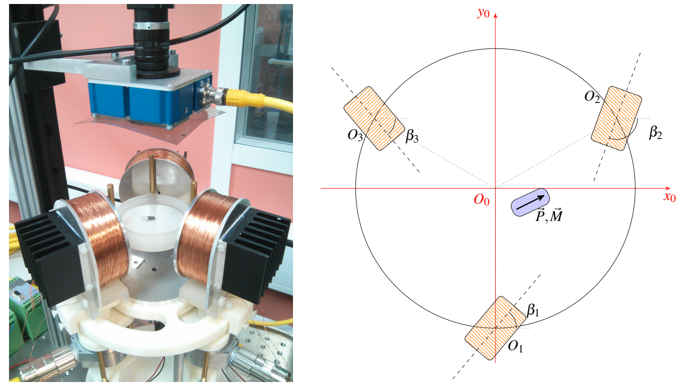
	Measures	**Finite element**	**Dipole approximation**	**Hybrid model**
Memory used	↑↑	↑	↓↓	↓↓
Real-time	↓↓	↑↑	↓↓	↓
Set up time	↑↑	↑	↓↓	↓
Accuracy	↑↑	↑↑	↓↓	↑

TABLE I. ELECTROMAGNET MODELING METHODS

III. USABILITY OF THE MODEL TO CONTROL A SYSTEM

The first way to use (3) is to compute the efforts produced by an electromagnet at a given point, for a given current. Thereby, it is easy to verify wether a system is able to produce the expected forces over the whole workspace. For instance, a system consisting of three electromagnets rotating about a vertical axis (Fig. 1) was simulated and shown to be capable of producing an effort of $0.3N$, needed to drive a capsule in the small bowel [5], throughout its workspace with a current not exceeding $2A$ in each coil.

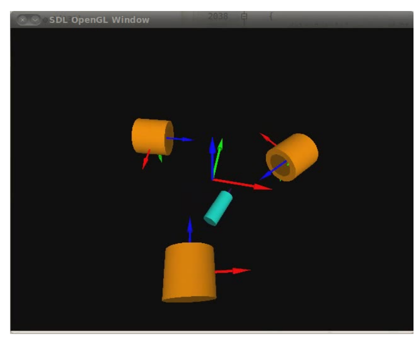
The second way to use (3) relies on its analytical nature, and invert it to compute the current and the position of each electromagnet to achieve a given effort. This allows to implement the control system. The system in Fig. 1 permits the manipulation of a capsule in the plane (3 DOF) and has 6 inputs (3 currents and 3 orientations). This redundant system allows to develop commands to optimize the manipulation of the capsule while optimally positioning the coils to achieve the efforts needed. This control method has been tested in simulations [6], and is now being implemented on a prototype.



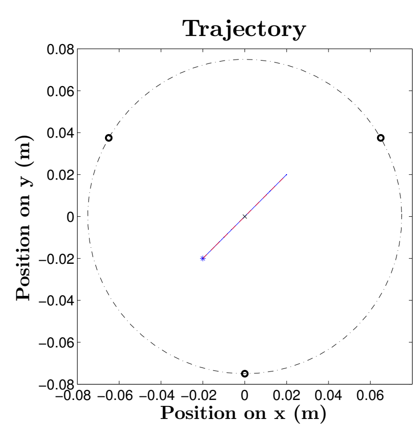
(a) (b)

Fig. 1. (a) System studied, and (b) diagram of this system (top-view).

An example of results obtained with such a simulation is shown on Fig. 2 and Fig. 3. In this simulation, the expected trajectory is perfectly realized with an error in position less than a tenth of a millimeter (Fig. 3(a)), and an error in orientation less than one tenth of a degree (Fig. 3(b)). Note that these simulation results were obtained by including disturbances on the detection of the capsule, the positions of the coils, and the currents in the coils.

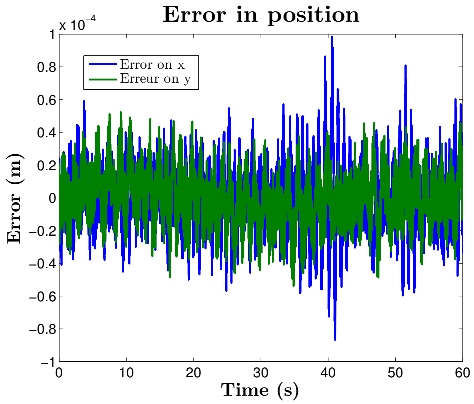


(a) Simulator.

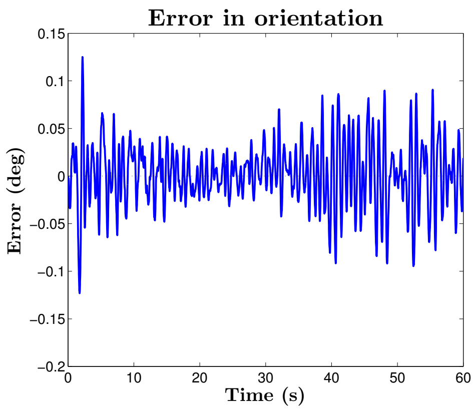


(b) Trajectory.

Fig. 2. Simulation of the system studied on a planned trajectory.



(a) Error in position.



(b) Error in orientation.

Fig. 3. Errors on the position and orientation of the capsule obtained along the trajectory Fig. 2.

Furthermore, this method can be extended to more complex systems. One can imagine a system such as that shown in Fig. 4. Its configuration can be adapted to the part of the body wherein the object is manipulated, to realize the best control.

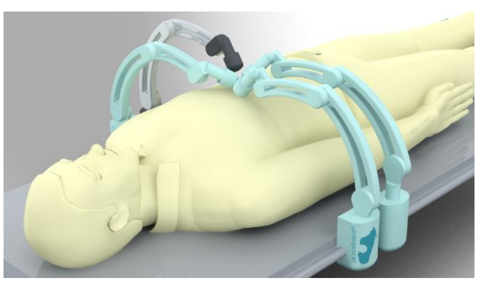


Fig. 4. Artistic view of a reconfigurable system with mobile electromagnets.

IV. Usability of the Model for Design Optimisation

From another point of view, this model can also be used to optimize the design of a system. Thanks to their high precision, finite element models are usually used for this purpose, but these calculations are time consuming, requiring to select a limited number of parameters for the optimization.

Model (3) allows faster computation while maintaining good accuracy. For example, for a single electromagnet the finite element model is extremely simple since it is reduced to an axisymmetric simulation. In this case, model (3) needs 80% less computation time. In 3D systems, computation time exponentially increases in finite element simulations. This highlights the usefulness of an analytical model for optimization of complex systems.

V. Conclusion

We have shown the importance of efforts for non-contact manipulation. Better control of these efforts ensures the manipulability of the object, which benefits both the patient whose safety is ensured, and the medician for whom the manipulation of the capsule is simplified, more reliable, and more accurate.

Electromagnets make sense when it comes to producing magnetic efforts by taking into account access to the patient by medical staff. Indeed, the system must be lightweight and not bulky, while enabling to produce efforts powerful enough to overcome any blocquage of the object (for endoscopic capsule, the passage of a sphincter for instance). The hybrid model developed here allows easy calculation of the magnetic efforts in real time, as well as the control system composed of such electromagnets. This promotes the automation of some procedures, such as navigation in the stomach before a physician performs the passing of the pylorus.

We also showed that this model allows to optimize the design of the system, ensuring that all the movements of the capsule are possible at any point of the workspace.

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