Physics-Based Simulation and Control Framework for Steering a Magnetically-Actuated Guidewire

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***Abstract*—This paper establishes a physics-based simulation framework for steering a magnetically actuated guidewire based on the linear elasticity and dipoles theories. Interaction wrenches resulting from an external magnetic field and embedded magnet filed within a continuum rod, i.e., guidewire serves as actuators for steering. In the presented framework, a simplified integration scheme based on the finite-volume method is employed to model guidewire using the linear elasticity theory and forces resulting from the interference of magnetic fields to provide a rapid model reconstruction. Furthermore, orienting the external magnetic field is employed to steer a guidewire into a constrained environment. Finally, simulations illustrate the approach performance on a soft rod where an external magnetic field is orientated to form the desired shape for a continuum rod and steer it within an environment. The results open up possibilities to construct a rapid model for continuum manipulators in practice.**

***Index Terms*—Soft robotics, continuum manipulator, Magnetic, Shape formation, multiphysics simulation**

I. Introduction

Modeling and simulation of multiphysics phenomena have attracted the attention of researchers in recent decades with the help of advances in computing performance. The multiphysics simulations by taking into account criteria such as geometrical constraints and mechanical properties. These algorithms can be employed to cope with the difficulties of modeling continuum robots in which various actuation mechanisms are employed.

Soft continuum robots have flexible and stretchable bodies with infinite degrees of freedom, increasing the complexity and maneuverability of robots in a workspace. Modeling these highly complex robots is computationally heavy due to complex geometries and coupled actuation mechanisms such as thermal, electrical, or magnetic actuators. In other words, soft robots may be coupled with other physical fields for actuation purposes, and therefore these physical fields should be taken into account in the modeling.

For continuum manipulators, several actuation mechanisms have been taken into account in the literature such as cable-driven [1]–[3], thermal [4], magnetic actuation [5] in different applications, e.g., . Table I summarizes recent work on shape formation or simulation of continuum manipulators with different actuation mechanisms.

TABLE I
STATIC SIMULATIONS OF CONTINUUM MANIPULATORS

Reference	Modeling Approach	Robot
[6]	piecewise-constant curvature	2-DoF tendon-driven robotic guidewire
[7]	kinematic model considering segments and tension-sensing cable	Cable-Driven Continuum robot with interlocked segments
[8]	Static simulation based on Cosserat rod model in three dimensions	Continuum strands
[9]	Static simulation based on group theory formulation	Intervascular shaping operations
[10]	A finite element based simulation with considering large deformations	A general surgical continuum manipulator
[11]	Static simulations with loads in three dimensions based on Cosserat rod model	A general surgical continuum manipulator
[12]	Static simulation based on linear elasticity theory	A Tendon driven continuum manipulator
[13]	Static simulation analysis based on virtual-work and screw theory	Multiple backbone continuum manipulator
[14]	Static simulation based on beam mechanics and elestic energy theory	Concentric tube manipulator

Shape formation of a continuum manipulator can be addressed through model-based [2], [15] and model-free approaches [16]–[18]. Although precise modeling of soft robots may lead to a robust control or motion planning, these algorithms [15] are usually based on numerical methods and target to find solutions for (partial) differential equations and therefore require extensive computational resources. In addition, it may not be feasible to run those algorithms in real-time. On the other side, model-free approaches do not guarantee any level of performance, especially in the presence of uncertainties in robots workspace. Therefore, the prevalence of modeling for soft manipulators in real-world applications necessitates developing rapid and intuitive simulations.

This study makes a contribution by presenting a rapid quasi-static modeling technique for simulations of soft manipulators control and formation. This article proposes rapid multiphysics simulation framework for magnetically actuated continuum manipulators within an environment similar to GI tract for closed-loop control applications to reduce the reality gap. The suggested technique is unique in that it combines rapid quasi-static models with soft guidewires controlled by magnetic fields, which may be employed in closed-loop control systems for precise navigation.

The paper is organized as follows. The problem statement is briefly discussed in Section 2. Section 3 is devoted to introducing the approaches we employed for a rapid simulation. Simulations have also been carried out to test the efficiency of the proposed solver in Section 4, and discussions and conclusions are reported in Section 5 and 6, respectively.

II. Problem Statement and Motivation

Consider a guidewire into which a permanent magnet is embedded as an actuation point. The guidewire will be shaped to go through a Gastrointestinal (GI) tract structure by applying external magnetic fields through single or multiple permanent magnets. Firstly, a fast, controllable model for magnetic wrenches is developed where each permanent magnet is modeled as one or multiple dipoles. Secondly, for the guidewire, multiple joints are considered on the wire where they are modeled as rotational springs (to capture the bending potential energy), and segments in between the joints are modeled as a linear spring. Finally, the interaction of the manipulator and its surrounding tissues, i.e., friction, has been incorporated into the manipulator model. The presented model can be used to model both stiff and soft continuum manipulators. In the presented framework, the objective is to steer a guidewire into an intervascular-like structure.

III. Method

This section presents a framework for the simulation of a soft continuum manipulator based on the linear elasticity theory.

A. Magnetic Interaction Modeling

In general, calculating interactive magnetic wrenches between two magnets is a very complex problem, and they depend on the magnetization, shape, and pose of magnets. In other terms, for accurate calculations of the wrenches, numerical methods are employed. Nevertheless, light and real-time models for calculating the wrenches are essential when magnets are used in a control loop as model uncertainties and errors are compensated by designing suitable controllers. In this study, and for simplicity, magnets are represented by dipoles. Forces at position $\bar{d}$ resulted from the interaction of two dipoles with magnetic moments $\bar{\mu}_1$ and $\bar{\mu}_2$ are the same in magnitude with opposite directions can be written as $F = \frac{3\mu_0}{4\pi d^5}\Big[\bar{n}_1\bar{\mu}_2 + \bar{n}_2\bar{\mu}_1 + <\bar{\mu}_1, \bar{\mu}_2> \bar{d} - \frac{5}{d^2}\bar{n}_1\bar{n}_2\bar{d}\Big]$ where $\bar{n}_1 = <\bar{\mu}_1, \bar{d}>$, $\bar{n}_2 = <\bar{\mu}_2, \bar{d}>$, $d = \|\bar{d}\|_2$, and $\|\cdot\|_2$ denotes norm 2. The magnetic torque of the dipole $\bar{\mu}_2$ acting on the dipole $\bar{\mu}_1$ is defined as $\bar{\tau}_1 = \bar{\mu}_1 \times \bar{B}_2$. in which $\bar{B}_2$ is the magnetic field of the dipole $\bar{\mu}_2$ and is defines as $\bar{B}_2(\bar{d}) = \frac{\mu_0}{4\pi}\Big[\frac{3\bar{d}}{d^5}\bar{n}_2 - \frac{\bar{\mu}_2}{d^3}\Big]$. In addition, the magnetic torque of the dipole $\bar{\mu}_1$ acting on the dipole $\bar{\mu}_2$ can be found in a similar way.

The effects of a magnetic force resulted from an attraction field between two aligned dipoles and the magnetic torque resulted from the misalignment of two dipoles are shown in Figures 1 and 2, respectively. In other words, by moving the free dipole toward the constrained dipole, the beam bends due to the magnetic force resulted from an attraction field. Furthermore, by rotating the free dipole in place, the beam deflects from its original position due to the magnetic torque resulted from the misalignment of two dipoles.

B. Guidewire Modeling

A guidewire is modeled as multiple segments and joints such that each segment is modeled as an extensible spring, and joints are modeled as rotational springs, which allow the guidewire to bend in the three dimensions. The embedded magnet into the tip of the guidewire is considered as a rigid body. Since guidewires are usually thin; therefore, twisting is not considered in the modeling. The model is shown in Figure 3, and the modeling procedure is summarized in Algorithm 1.

C. Steering Setup

A single external magnet is employed in this study to introduce forces to the tip for steering purposes. The proposed setup is shown in Figure 4.

The external magnet is modeled as a set of dipoles (2000 dipoles) rotating around y-axis and Figure 5 shows the resulted flux and the applied force on the tip dipole and the projected force on the spline.

IV. Simulation Results

In this section, we consider a permanent magnet modeled as a dipole embedded into the tip of the guidewire. The presented setup, including an external magnet modeled as 2000 dipoles, is located at a 7 cm distance from the GI tract. The idea is to rotate the external magnet to steer the guidewire toward a desired location inside a GI tract structure, as in is shown in Figure 3. Length and diameter of GI tract structure are 8×10^{-1} m and 1.5×10^{-2} m. The tip embedded neodymium magnet is a cylindrical magnet with a diameter of 2 mm, height 3 mm, weight 7.2×10^{-5} kg, and residual magnetism 1.37 T. A circular cross-section guidewire with the radius 2.5×10^{-3}, Young modulus constants 550 and 600 KPa for rotational and linear springs are considered, i.e., rotational and linear spring constants are 10.79 Nm^{-1} and 11.78 Nm^{-1}, respectively. For the external magnet, a block magnet 50.8 mm $\times$ 50.8 mm $\times$ 50.8 mm with residual magnetism 1.3 T is considered. Furthermore, it should be noted that as boundary conditions, the guidewire is always locked to the direction of the GI tract, i.e., tangent to the GI

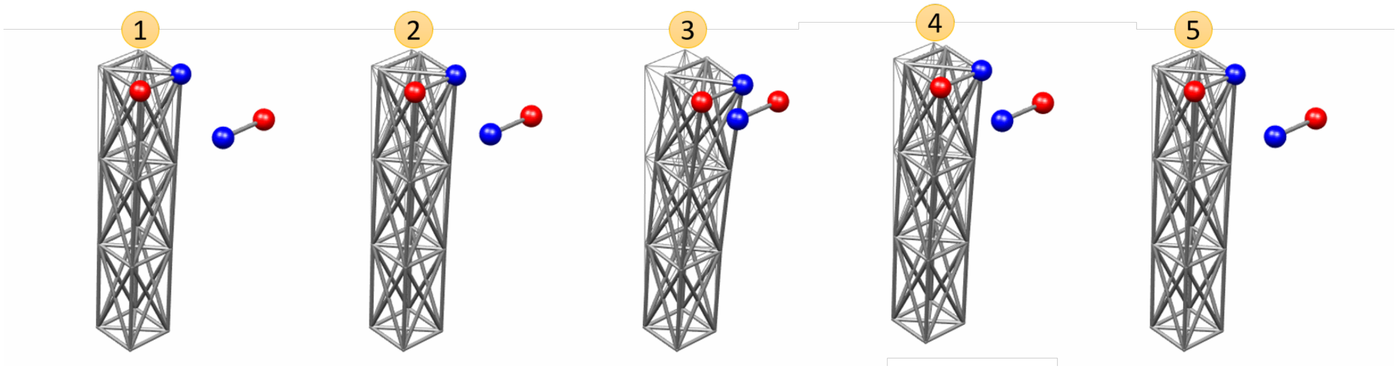

Fig. 1. By moving the free dipole toward the constrained dipole, the beam bends due to the magnetic force resulted from an attraction field.

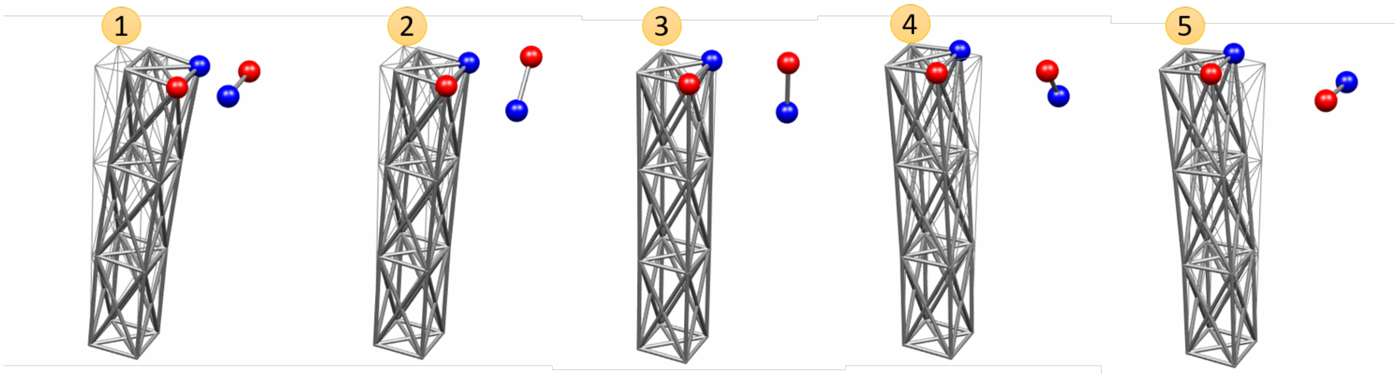

Fig. 2. By rotating the free dipole in place, the beam deflects from its original position due to the magnetic torque resulted from the misalignment of two dipoles.

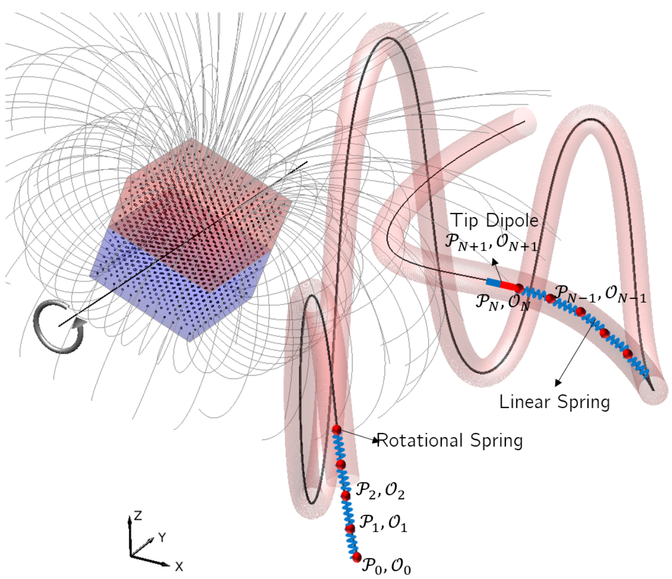

Fig. 3. A guidewire is partitioned into multiple segments and joints: Each segment is modeled as a linear spring and joints are modelled as rotational springs.

tract and can not bungle up inside the environment as it has been mentioned in the last step in Algorithm 1.

For the simulation, the external magnet only has a rotational

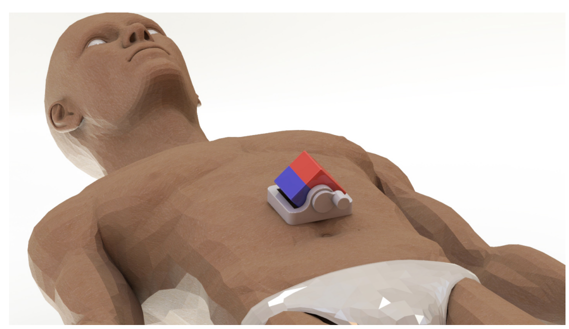

Fig. 4. Proposed steering setup including an external magnet.

movement. Figure 6 shows projected forces tangent to the GI tract structure obtained from different rotation angles. The maximum projected force on the spline curve resulted from a specific rotation angle is depicted in Figure 7. In other words, Figure 7 depicts the maximum projected force applied to the dipole embedded at the tip of the guidewire resulted from a specific rotation angle of the external magnet at each position of the GI tract.

V. Discussion

It was the primary purpose of the paper to draw attention to the magnetic navigation of a guidewire or catheter inside a complex environment such as the GI tract. The authors

Initialize:
Define a spline curve within the GI tract structure;
Orientation of joints in rest state on spline:
$\{\mathcal{O}_0, \cdots, \mathcal{O}_{N+1}\}$;
Position of joints in rest state on spline:
$\{\mathcal{P}_0, \cdots, \mathcal{P}_{N+1}\}$;
Initial velocity of joints are zero;
Boundary conditions are considered free at the both end;
while *simulating* **do**

i. Apply external magnetic forces on tip dipole (attached magnet to the tip) alongside with the spline;
ii. Integrate tip magnet position;
iii. Enforce tip magnet position coupling to the rest of the guidewire;
iv. Calculate spring forces between guidewire segments due to segment length deviations by using a spring constant;
v. Calculate bending forces between wire segments (at joints);
vi. Integrate joints poses;
vii. Project all joints forces to the direction of the corresponding guidewire segment (alongside with the spline);
viii. Update joints position;
ix. Snap all joints onto the closest spline;

end

Algorithm 1: Guidewire simulation.

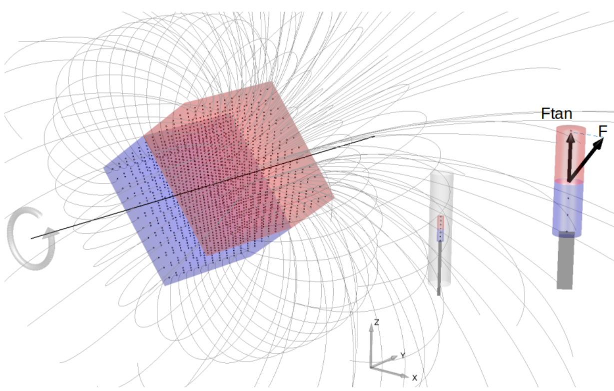

Fig. 5. A rotating external magnet modeled as 2000 dipoles. the resulted flux and the applied force on the tip dipole and the projected force on the spline.

attention was concentrated not only on designing a multiphysics simulation framework to model soft guidewires and magnetic fields and forces but also on showing possibilities for applying the proposed framework in minimally invasive surgeries. The originality of the proposed solution lies in the fact that it combines fast quasi-static models soft guidewires actuated with magnetic fields where this model can be used in closed-loop control systems for accurate navigation.

The results obtained are broadly in good agreement with the major trends of magnetically actuated manipulators. In other words, the main finding in this study is that we only need one magnet and one axis of rotation to move the tip of a guidewire in any direction in 3D space as long as the guidewire tip is aligned with (tangent to) the GI tract. This is not very intuitive that with only one input parameter, the system is capable of dragging a guidewire in the 3D space.

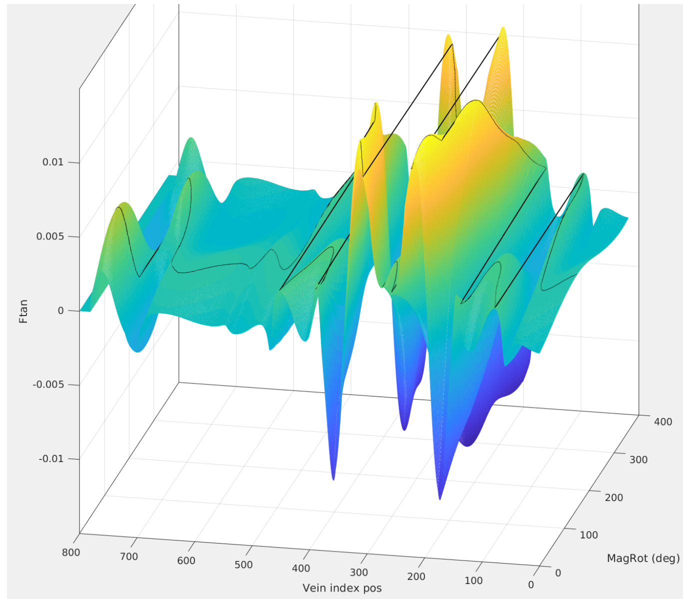

Fig. 6. Projected force (N) applied to the guidewire tip dipole alongside the GI tract resulted form orientation of the external magnet with respect to the rotation of the external magnet at different locations of the GI tract i.e., the GI tract index positions. Maximum projected force applied to the dipole embedded at the tip of the guidewire is shown by the solid black curve.

The findings have a number of possible limitations, namely, force magnitude inserted on intestines or the force magnitude might not be enough for moving the tip magnet; finally, geometry and the number of the external magnets affect the produced forces on the tip. Also, torques on the tip are not desired in the considered scenario, meaning that torques can deviate from the tip for the defined spline curve. Therefore, by adding more degrees of freedom to the system, such as increasing the number of external magnets and considering transnational movements of external magnets, the magnitude of the projected force can be increased, and undesired effects of torques can be weakened.

VI. Conclusion

The article demonstrates the possibility of steering a guidewire by rotating an external magnet inside a complex environment. The proposed simulation framework results should be applicable also to different scenarios where the number of external magnets and their geometries are customized. Also, the results open up possibilities to construct a rapid model for magnetically actuated continuum manipulators for closed-loop control applications to reduce the reality gap. Clearly, further research will be needed to validate the results. Therefore, the next stage of this research will be the experimental confirmation of the presented framework. Future work will involve consider-

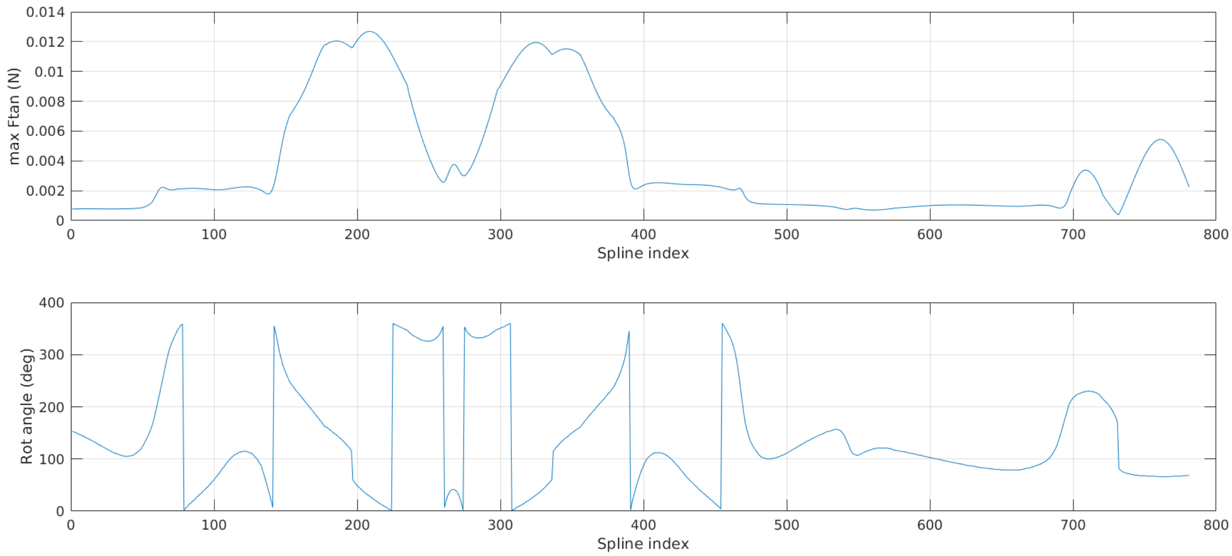

Fig. 7. Maximum projected force applied to the dipole embedded at the tip of the guidewire resulted from a specific rotation angle of the external magnet at each position of the GI tract.

ing more external magnets as actuators together with difficult-to-reach environments.

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