Computational Predictive Model for Full Body Controlled Soft Continuum Magnetic Robots Under Hybrid Actuation

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INTRODUCTION

In recent years, medical microrobots have emerged as a non-invasive solution to many medical interventions [1, 2]. Soft continuum magnetic robots (SCMRs), a class of soft robots, were introduced as a promising method for endovascular intervention [1]. The small scale, adaptability, flexibility, and high controllability of SCMRs made them well suited for the clinical applications.

The SCMRs originally introduced for endovascular intervention [1, 3], however, utilised rigid permanent magnets within their structure, increasing the risk of vascular trauma during deployment. Therefore, fully soft continuum magnetic robots (FSCMRs), made of magneto-responsive soft material, were introduced to improve their clinical implementation [4].

Imparting a lengthwise magnetisation profile into FSCMRs, full body shape forming is possible under application of homogeneous magnetic fields, improving conformation to anatomical structures. Shapes have been predicted for homogeneous electromagnet (EM) generated fields using computational models [5], and through permanent magnet (PM) actuation with mathematical models [6]. However, the whole-body modelling of FSCMRs under actuation via combinations of PM- and EM-generated fields has not been explored.

The presented study introduces a computational model to capture FSCMR shape-forming via independent and simultaneous PM (up to two) and EM actuation. The accuracy of this model is validated with the experimental data.

EXPERIMENT SETUP

The experimental setup consists of three main parts (shown in Fig. 1): (1) an EM external magnetic field generator (MFG100 system), two robotic arms (DoBot Magician), camera (Basler, puA1280-54um) and a computer for monitoring); (2) FSCMRs with a diameter of 600 µm and length of 25 mm; and (3) a 3D-printed 120 mm square test bed and FSCMR holder, arranged to align its centre with the centre of FSCMR and the EM field generator, and 3D-printed holders to host the PMs and attach to the robotic arms.

SIMULATION

COMSOL Multiphysics (V. 6) software was used for computational modelling of the FSCMR within inhomogeneous magnetic fields, using the mechanical properties introduced in [5]. Simulated magnetic fields were produced to match three distinct actuation scenarios: (i) one PM; (ii) two PMs; and (iii) hybrid system consisting of one PM and the EM system. For each scenario a range of actuation parameters were tested, varying the PM position and direction, and EM field magnitude and direction.

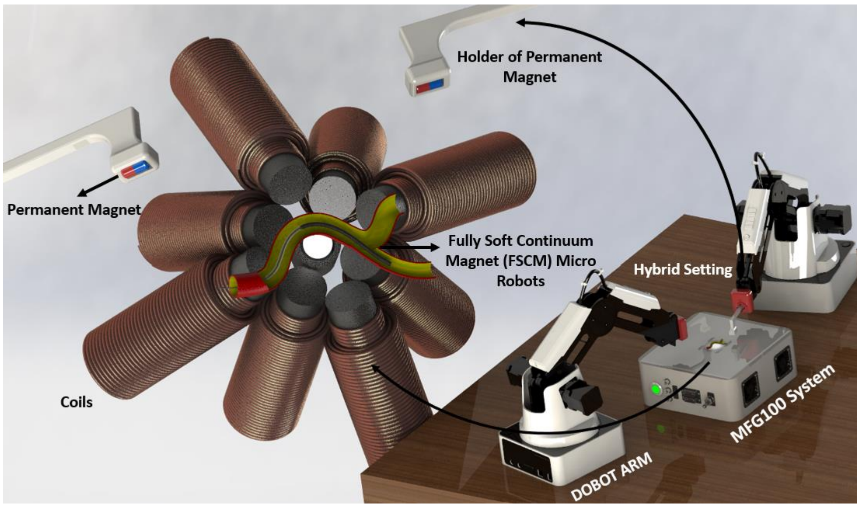

Fig. 1: Conceptual figure of the systems for full body control of the FSCMs.

VERIFICATION

The experimental range bounded the PM movement from 20 mm to 45 mm (x direction) with 5 mm steps and from -45 to 45 (y direction) with 5 mm steps and covered the three scenarios introduced above. Each scenario and parameter combination were simulated using the computational model and replicated experimentally, with the FSCMR in an aqueous environment. Image processing (MATLAB, MathWorks, USA) was used to extract FSCMR shapes from the experimental and computational data for comparison. To assess the

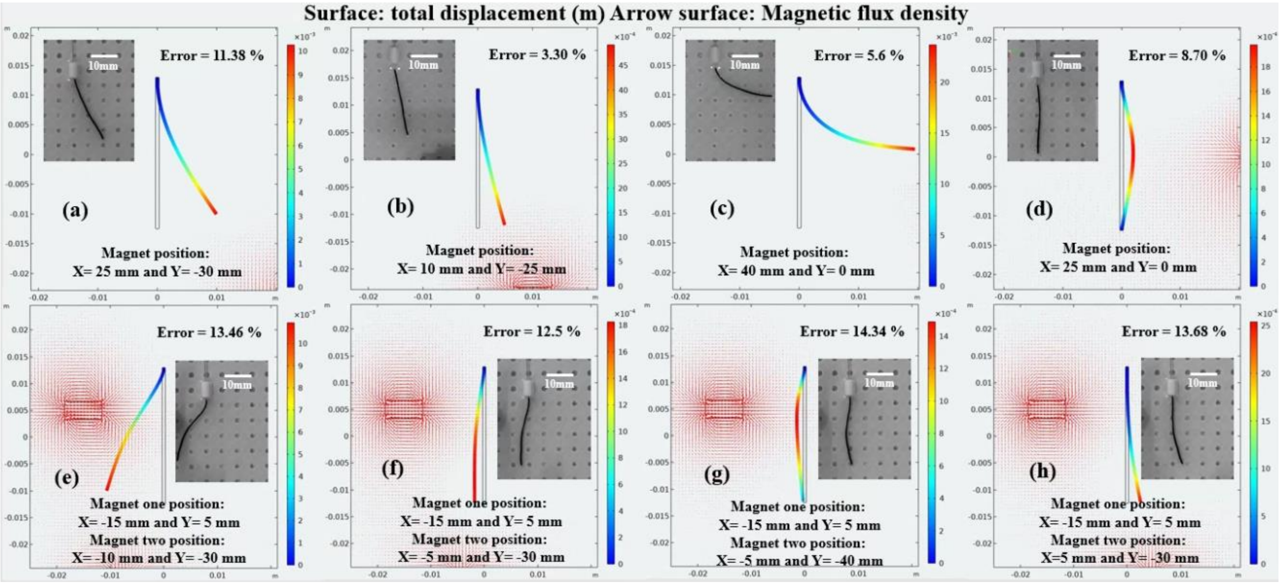

Fig. 2: Simulation and experimental shapes of the FSCMRs in different conditions. The tip position error of FSCMs between experiment and simulation are showed in each image. (a), (b), and (c) One PM with a pull effect; (d) one PM with a pull effect and electromagnet with a magnitude of 3 mT; (e), (f), (g), and (h) two PMs with a pull and push effect.

suitability and accuracy of the proposed numerical platform, two parameters were considered: (1) the shape classification of the FSCMR, and (2) the tip position of the FSCMR. Shape classification was evaluated based on attainment (through polynomial fitting) of one of eight independent shape categories, identified from the range of experimental data (as illustrated in Fig. 2). Tip position accuracy was calculated as 89.63 % ($e = \frac{\bar{r}_{exp}-\bar{r}_{sim}}{\bar{r}_{exp}}$, where index exp and sim indicate experiment and sin shows the simulation results, and r is the tip vector of the FCSMs that is $\sqrt{x^2 - y^2}$).

Fig. 2 shows comparisons for eight body shape categories, with tip deformation errors ranging from 3.3% to 14.34%. In scenario one (one PM), 20 permanent magnet positions were studied, resulting in 85% similarity in shape classification with a 5.34% tip position deviation. In scenario two (two PMs), 15 different positions with three different effects were tested, resulting in 82% shape similarity with an 11.61% tip position deviation. In the hybrid (PM-EM) implementations, shape classification had similar results in all cases, with an average tip position deviation of 12%. Although the error level in predicting the tip position of the soft robot may seem high in some cases, it is considered an acceptable error since it does not result in any physical contact between the robot's tip and the boundary of the vessel.

DISCUSSION AND CONCLUSION

A computational model has been proposed in this academic paper for predicting the shape of a soft robot under different actuation scenarios using the COMSOL software. The accuracy of the platform has been assessed through experimental data, and the results indicate that the model has an acceptable accuracy in predicting the shapes and tip positions of FSCMRs under a hybrid actuation system. Although there were some discrepancies between the predicted and experimental data, the errors were deemed acceptable as they did not result in collisions with the vessel wall. Overall, the proposed computational model can be used as a predictive tool for designing or guiding soft magnetic robots under more versatile hybrid actuation scenarios, while preventing them from contacting hypothetical boundary constraints.

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