Dual-Arm Platform for Control of Magnetically Actuated Soft Robots

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INTRODUCTION

The present work discusses a novel approach for remote magnetic actuation. In the following, we present a full characterization of the dual External Permanent Magnet (dEPM) actuation system. Herein, we discuss how this system can be applied to fully control the magnetic field in a predefined workspace. We discuss how it can generate a *homogeneous magnetic field*, in every direction and control every *independent* gradient in the same workspace. We prove how up to 8 Degrees of Freedom (DOF), 3 independent field components and 5 gradients directions, can be controlled fully independently.

The rise in popularity of magnetic actuation comes from the fact that it allows for the control of wireless magnetic micro-robots and magnetic Soft Continuum Robots (SCRs), which bring about a reduction in size when compared to their non-magnetic counterparts. SCRs have a theoretical infinite number of DOFs and thus, can adapt to various nonlinear environments, minimising contact and pressure on surrounding tissue. While successful multi-DOFs magnetic actuation has been demonstrated at small scale [1], by using systems of *coils*, large-scale manipulation is yet to be fully proven. In fact, it might require several independently-controlled coils [2] to be effective along any possible direction of motion. Despite their ability to generate both homogeneous fields [3] and gradients [2], systems of coils are less scalable, compared to permanent magnet-based magnetic field control systems [3]. In fact, due to lower field density, energy-consumption and need for high-performance cooling systems, they are generally characterized by limited workspace [4].

By further developing the idea of remotely actuating 1 Internal Permanent Magnet (IPM) (internal since, generally, inside the human body) with 1 External Permanent Magnet (EPM) [5], we discuss how 2 robotically actuated EPMs are able to magnetically manipulate 2 IPMs, independently. This is achieved by independently controlling the torque (magnetic field) and the force (field gradients) applied to each IPM.

MATERIALS AND METHODS

Magnetic manipulability is the measure of the number of magnetic DOFs that can be magnetically manipulated by a magnetic actuation system. This means that, given a set of inputs, we aim to measure the number of variables that can be independently actuated. In the following, we prove that with 2 EPMs (M = 2) we can control 8 DOFs of 2 orthogonal IPMs (N = 2) in the same point of the worskspace. Assuming that 2 IPMs are in the same point within the workspace, they will experience the same magnetic field (B) and magnetic field jacobian ($dB = \frac{\partial B}{\partial p}$). This will induce a magnetic wrench on the IPMs consequent to its magnetization m_i and location p_i as shown in (1).

$$w_i = \begin{pmatrix} 0_{3,3} & m_{i_+} \\ m_{i_\times} & 0_{3,5} \end{pmatrix} \begin{pmatrix} B(p) \\ dB(p) \end{pmatrix}. \quad (1)$$

$$w_i = S_i U$$

Where $w_i = \begin{pmatrix} \tau_i \\ f_i \end{pmatrix}$ and τ_i and f_i and refer to the respective torque and force on the agent i. Here we introduce the operator $\cdot_+ : \mathbb{R}^3 \to \mathbb{R}^{3\times5}$ which rearranges any vector $v \in \mathbb{R}^3$, as well as the operator $\cdot_\times : \mathbb{R}^3 \to \mathbb{R}^{3\times3}$ as $v_\times = (v \times e_1 | \; v \times e_2 | \; v \times e_3)$. Where e represents the canonical basis of $\mathbb{R}^3$.

Finding the rank of S allows us to determine the number of controllable DOFs. It is known that for any agent i, $rank(S_i) = 5$ [6]. Moreover, one can notice that maximum manipulability can be obtained when the 2 agents are orthogonal. This comes from the fact that with this configuration $S = ({S_1}^T {S_2}^T)^T$ and $m_1 \times m_2 \neq 0$. Resulting in $rank(S) = 8$, thus proving that with $M =$

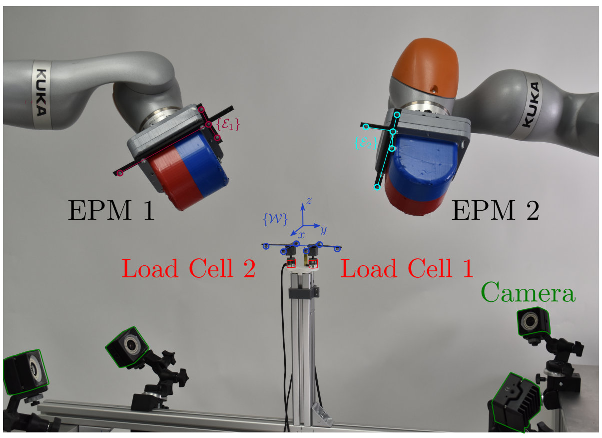

Fig. 1 Setup for magneto-mechanical actuation experiments using the dEPM setup

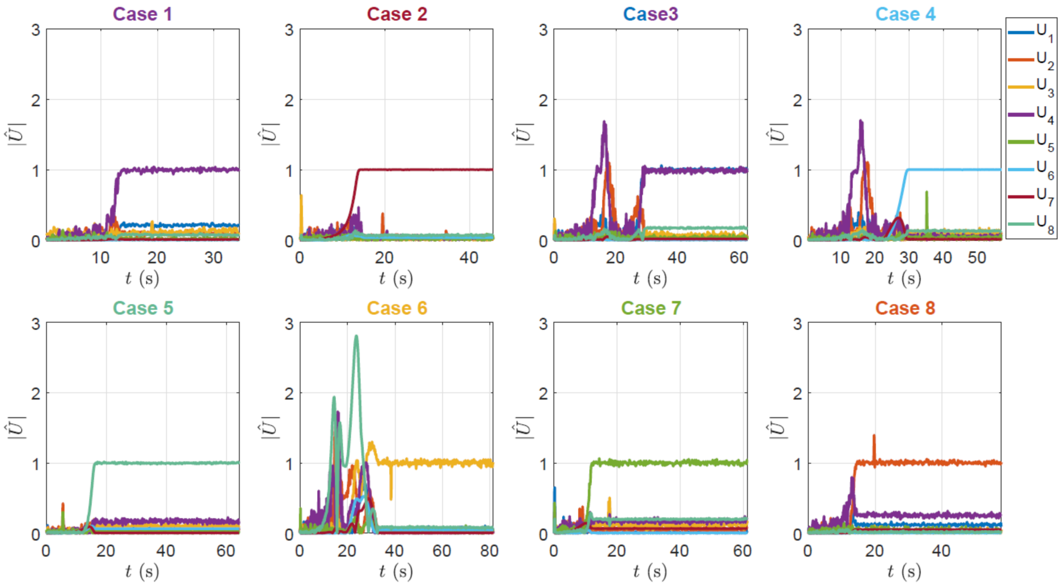

Fig. 2 Normalized response for magnetic field and differentials. Title colors are referred to the component activated for each case.

$N = 2$ we can control 8 independent magnetic DOFs. Since 2 EPMs are used, we refer to this actuating system as the dEPM system.

Finding 8 independent DOFs is equivalent to finding 8 poses of the EPMs that lead to 8 orthogonal directions of the wrench onto the IPMs. Thus, obtaining 8 independent $U(T)$, where $T = 1, 2, ..., 8$. Due to the nonlinearities associated with solving (1), we opted for a direct analysis of primitive poses which show independent activation of field and differential component. To achieve *independent field control* we look for configurations where the magnets are aligned. In contrast, to obtain independent components of U related to the *differentials* of the field, we consider solutions with no field components. This is achieved by positioning the EPMs in opposite directions.

RESULTS

Validation of the proposed inferences were performed through a series of experiments, aimed at proving the 8 DOFs manipulation capabilities. This was done by using 8 configurations of the EPMs for which we can control, independently, the 8 components of the field U. Each experiment was performed by placing 2 IPM coupled 6-axis load cells ($12.7 \times 12.7 \times 12.7$ mm^3 Nano17 Titanium, ATI, USA) between 2 robotic arms (LBR iiwa 14, KUKA, Germany); each manipulating one of the actuating EPMs (Cylindrical permanent magnet with a diameter and length of 101.6 mm and an axial magnetization of 970.1 Am^2 (N52)), as shown in Fig. 1. Two load cells where used, each with a IPM attached to it, with IPMs orthogonal to each other. By measuring the wrench induced by each unique pose of the EPMs and inverting (1) by use of the Moore-Penrose pseudoinverse, U for each pose was measured. The normalized results for each case (independent actuation of each component of U) can be seen in Fig. 2.

DISCUSSION

The present work discussed the manipulation capabilities of robotically manipulated magnetic sources. In particular, we showed that 2 actuated EPMs are able to independently manipulate 8 DOFs. Both theoretical dissertation and experiments prove that the proposed approach can achieve the same capabilities as coil based actuation [6]. The findings can be used to potentially improve a vast range of diagnostic and interventional medical procedures through the employment of smaller and softer instruments. For example, applying the dEPM system to actuate multi-DOFs magnetic SCRs.

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