A Magnetically-Actuated Coiling Soft Robot With Variable Stiffness

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Abstract—Soft and flexible magnetic robots have gained significant attention in the past decade. These robots are fabricated using magnetically-active elastomers, are capable of large deformations, and are actuated remotely thus allowing for small robot size. This combination of properties is appealing to the minimally invasive surgical community, potentially allowing navigation to regions of the anatomy previously deemed inaccessible. Due to the low forces involved, one particular challenge is functionalizing such magnetic devices. To address this limitation we introduce a proof-of-concept variable stiffness robot controlled by remote magnetic actuation, capable of grasping objects of varying sizes. We demonstrate a controlled and reversible high deformation coiling action induced via a transient homogeneous magnetic field and a synchronized sliding nitinol backbone. Our soft magnetic coiling grasper is visually tracked and controlled during three experimental demonstrations. We exhibit a maximum coiling deformation angle of 400°.

Index Terms—Grasping, magnetic continuum robots, soft robots, surgical robotics, magnetic actuation, continuum manipulators.

I. INTRODUCTION

Soft magnetic robots, due to an inherent reduction in traumatic anatomical forces, display the potential to supersed traditional mechanically-actuated minimally invasive surgical instruments [1], [2], [3]. The ability of these robots to manoeuvre through delicate and critical anatomy in a minimally invasive manner is key to improving the feasibility and success of many treatments [4]. Magnetic actuation allows devices to be composed of softer materials as forces and torques can be applied directly to embedded magnetic material as opposed to lengthwise force transmission [5], [6]. Furthermore, this class of rapid and clinically safe actuation eliminates the need for on-board power transmission systems (such as electrical or pneumatic) allowing easy miniaturization [7].

In order to introduce shape-programmability, magnetically-hard particles with high coercivity can be incorporated into mechanically soft materials capable of large deformations [8], [9], [10]. This system is capable of creating complex time
varying shapes at small scales as magnetic field control inputs can be specified in magnitude, direction and spatial gradient [11]. Magnetic soft continuum structures can also be fabricated with a continuous lengthwise magnetization profile thus generating spatially resolved deformations [11]. A range of applications have been demonstrated using this approach [7] including, amongst other applications, autonomous navigating catheters [6], cilia-like shape forming structures [11], untethered swimmers [10], shape forming catheters [12], [13], and untethered grippers [14].

Softness represents a clear advantage for medical tools [15], however, this can also be problematic when it comes to performing functional tasks. As such, variable stiffness becomes a highly desirable feature such as the magnetic catheter with conductive shape memory polymer demonstrated in [16]. There are many approaches to achieve stiffening, most commonly; geometric changes such as modifying the cross-sectional profile, elastic changes such as phase transition or jamming and antagonistic actuation [17]. The typical motive for stiffening in continuum robots, however, is to shape-lock after actuation [18]. Our design, on the contrary, offers a system which is shape locked prior to actuation and mechanical stiffening during the coiling phase is provided by the magnetic actuation itself. This is a novel stiffener/actuator arrangement with potential for future development using alternative stiffening technologies such as the temperature based bulk material property varying systems in [19] and [20] or the magneto-rheological stiffening demonstrated in [21]. Low melting point induced variable stiffness was exploited in [19] to achieve stable high deformation bending (≈270°) under magnetic actuation. Here we demonstrate fully wrapped deformation (>360°) for a high grip strength grasping mode in a manner with greater potential for miniaturization.

In this proof-of-concept work, we employ material variable stiffness in the form of a sliding nitinol backbone which offers a stiffness change factor of close to 800. This movement is synchronistically controlled within a closed-loop with a time-varying actuating field (Fig. 1) for the novel purpose of constraining some proximal length of our robot against deformation whilst we actuate the remaining distal length (Fig. 2). This allows us to apply otherwise unstable combinations of magnetization and actuating field to achieve a forward time marching deformation, fully dependent on the previous pose. Consequently, we generate a higher strain equilibrium and achieve circular deformations greater than one full revolution. Our conceptual design shares some similarities with the pre-curved elastomers of e.g. [22]. However, the actuating magnetic field allows us to exploit soft elastomeric construction without a corresponding reduction in grasp strength.

As a proof-of-concept we have applied our innovation to the demonstrative example of reversible coiling for grasping or delivery. There exists a clinical role for minimally invasive cargo retrieval or delivery systems, either untethered [23], [24] or via endoscopic manipulators [25]. Furthermore, there is a demonstrable appetite for the automation and miniaturization of both approaches [26], [27]. Other grasping type designs have been demonstrated in the literature such as the pneumatically actuated systems in [28] and the electromagnetic coil of [29] but these systems are all limited to varying extents in their minimum size. Our high deformation, variable stiffness approach offers the potential for increased grasp strength per unit size over magnetic forceps-like designs [30] whilst still displaying potential for miniaturization. We demonstrate our grasping motion for cylinders of diameters ranging from 10-15 mm. Whilst this investigation is still very much at the feasibility stage of development and these cylindrical objects are therefore largely arbitrary, there is indication that these shapes and sizes would have medical relevance [31].

The contribution of this letter is the actuation of a potentially unstable magnetic robot with variable stiffness. Synchronized actuation and variable stiffness combine to achieve stable, large deformation shape forming. To prove the necessity of the inclusion of the sliding nitinol backbone, we also demonstrate the unsuccessful actuation of the robot without the inclusion of stiffening wires. Following experimental evaluations with different geometries, this system is implemented in an 80 mm long, 10 mm x 2 mm cross-section tongue-like robot which grasps and releases arbitrary objects via coiling.

II. THE VARIABLE STIFFNESS ROBOT

In this section, we detail the analytical design principles, the fabrication technique and the dual material characterization of our tongue-like, variable stiffness robot (VSR).

A. Analytical Design - Elastic Torque

We represent the flexible, unsupported region of the VSR as a serial chain of rigid links connected by planar (1 Degree of Freedom) rotational joints as a simplification of [32] and [33]. Any desired shape can be represented as a vector of joint angles \(\mathbf{q}\) where the length of \(\mathbf{q}\) is determined by the granularity of discretization (individual link length \(l\)) and the unconstrained length of the VSR, itself a function of time \((L = L(t))\). Elastic
joint torque is given as
\[ \tau_{elas} = \frac{Kq}{l}, \]  
where \( l \) is the virtual link length and \( K \) is the elastic stiffness given by
\[ K = E_{ME}I_{ME} + E_{BB}I_{BB}, \]  
with \( E_{ME} \) and \( I_{ME} \) as the Young’s modulus and the second moment of area for bending of the rectangular cross-section magnetic elastomer, and \( E_{BB} \) and \( I_{BB} \) are those of the circular cross-section backbone, respectively (See Fig. 2)
\[ I_{ME} = \frac{wh^3}{12}, \]  
\[ I_{BB} = \frac{n\pi r^4}{4}, \]  
with \( w \) as the elastomer width, \( h \) as the elastomer height, \( r \) as the radius of the support rods, and \( n \) as the number of support rods. When the nitinol backbone is withdrawn \( E_{BB} = 0 \) and the mechanical stiffness drops dramatically.

B. Analytical Design - Magnetic Torque
A magnetic dipole with moment \( \mathbf{m} \) in a homogeneous field \( \mathbf{B}(t) \) will experience a resultant magnetic torque proportional to applied field strength
\[ \tau_{mag}(t) = \mathbf{m} \times \mathbf{B}(t), \]  
where \( \mathbf{B}(t) \), \( \mathbf{m} \), \( \tau_{mag}(t) \) ∈ \( \mathbb{R}^3 \) (If \( \mathbf{B} \) and \( \mathbf{m} \) are constrained to the x-y plane then the cross product becomes effectively scalar). The body torque acting on any discretized segment (virtual link) of the VSR as a consequence of the interaction of the actuating magnetic field, and the deformed magnetization of that region of doped elastomer will produce deformation, and therefore be counteracted by the elastic properties of the material.

C. Analytical Design - Torque Balance
Assuming gravity to be zero, we can balance the elastic torque at any given virtual joint \( (i, \text{in a VSR of N virtual joints}) \) with the aggregation of magnetic torques on every distal virtual link in the VSR at any given time step
\[ \tau_{i,elas} = \sum_{n=1}^{N} \tau_{n,mag}. \]  

Consequentially, defining position along the robot length from the tip as \( S \), the magnetization \( \mathbf{m} \) at any point along the robot is defined as
\[ \mathbf{m} = |\mathbf{m}| \text{rot}_z \left( \frac{S}{\pi r} 180^\circ \right) \hat{x}, \]  
with \( \hat{x} \) the unit vector in the x direction, and \( \text{rot}_z(\cdot) \in SO(3) \) the rotation matrix about the z-axis. The resultant rotational speed of the actuating field is a function of the speed of retraction of the backbone.

Due to desired deformations greater than \( 360^\circ \), the presented solutions have sacrificed design flexibility and are capable of generating only the target circular shapes reported (with the exception of the lower energy deformation shown in Fig. 5). Other profiles could be generated using the same process but
would require diverse magnetization solutions as demonstrated in [10], [12].

D. Fabrication

The manual fabrication process is outlined in Fig. 4 and is based on [12]. A split mold was 3D printed (RS-F2-GPGR-04, Formlabs, USA) into which 0.75 mm diameter nitinol wires are embedded, and the arrangement is bolted and glued shut. The elastomer (Ecoflex-0030, Smooth-On Inc, USA) was mixed with neodymium-iron-boron (NdFeB) microparticles with an average diameter of 5 µm (MQFP-B+, Magnequench GmbH, Germany) in a 1:1 mass ratio giving a saturated remanence of 120 mT [34]. This composite was mixed and degassed in a high vacuum mixer (ARV-310, THINKYMIXER, Japan) at 1400 rpm, 20.0 kPa for 90 seconds. The mixture was injected into the mold and cured at room temperature for four hours. Upon demolding, the 0.75 mm diameter nitinol rods are removed.

The specimens were then secured in a circular 3D printed magnetizing mold before being subjected to a saturating uniform field of 4.644 T (ASC IM-10-30, ASC Scientific, USA). The bending radius of the circle about which the specimen is wrapped during magnetization is described in Section II-C and discussed in Section V. For Sample 1 this parameter was 7.5 mm and for Sample 2 it was 5 mm.

Finally, the holes from which the 0.75 mm diameter rods were removed are filled with free sliding 0.5 mm diameter nitinol backbone rods. The robot body is capable of large elastic strains before the onset of plastic deformation. Consequently, the post magnetization unactuated state remains uncurved, with or without the nitinol backbone.

E. Variable Stiffness Characterization

Using Ecoflex-0030 (Smooth-On Inc, USA) doped at 100% by weight gives $E_{ME} = 100$ kPa [34], $E_{BB} = 50$ GPa [35] and from (3) and (4) with $w = 2$ mm, $h = 10$ mm, $r = 0.25$ mm and $n = 2$ gives the elastic stiffness of the nitinol backbone ($K_{BB}$) and the magnetic elastomer ($K_{ME}$) as $K_{BB} = 3 \times 10^{-4}$ Nm$^2$, $K_{ME} = 7 \times 10^{-7}$ Nm$^2$.

This gives an analytical stiffness change factor of 765. In practice, no measurable bending deformation is observed at fields up to 50 mT in the backbone supported region of the VSR. Fig. 5 shows the VSR in a static actuating field with incrementally adjusted support positions - the point at which the backbone reaches is marked with a yellow triangle. This clearly demonstrates the absence of bending in any of the proximal, supported regions. Furthermore, Fig. 5 shows the lowest energy state of the sinusoidally magnetized VSR. Without forcing the robot into the coiled higher energy state using correctly coupled backbone retraction and time-varying applied fields we cannot achieve the large deformations with which we functionalize the system. The supporting video: S1 also illustrates the failure of the VSR to coil around an object and uncoil when the actuating field is applied sinusoidally but the sliding nitinol backbone is absent.

III. CONTROLLED ACTUATION

In this section, we demonstrate a proof-of-concept functionalization of our VSR.
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\( 20 \text{ mT) and the control variable } p_{B} \)

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Fig. 8. Closed-loop control demonstration of grasping and releasing objects placed at arbitrary locations and shown at different time instants \((t)\) for three cases: (a) Sample 1 with 15 mm diameter object. (b) Sample 2 with 12 mm object. (c) Sample 2 with 10 mm object. The four stages of the experiment occur between the successive time snippets in the following order: grasping phase; coiling action; uncoiling action; releasing phase. The yellow triangle represents the tip position of the nitinol backbone. Please refer to the supporting video: S3-S5 for the complete demonstration.

reverse to uncoil the VSR and release the entrapped object. Fig. 7 illustrates the complete closed-loop control system.

E. Grasping Force Characterization

A 3-axis force sensor (K3D40, ME-Meßsysteme GmbH, Hennigsdorf, Germany) is used to measure the grasping strength of the VSR. A cylindrical object is attached to the force sensor and the base of the VSR is connected to a linear stage. For different strengths of magnetic fields generated by PaCMag, the VSR is wrapped partially and fully around the object and retracted backwards at small increments using the linear stage. The force sensor records the grasping force on the object along the axial direction of the VSR until the grip fails and the VSR loses contact with the fixed object.

IV. RESULTS

The two VSR samples 1 (7.5 mm bending radius) and 2 (5 mm bending radius) are used to demonstrate the grasping and releasing of printed cylindrical objects in closed-loop as shown in Fig. 8. Three objects of diameters 15, 12 and 10 mm are placed at various locations facing the coiling side of the VSR. The VSR, initially in its straight configuration, wraps around the object to grasp it, coils further to move the object along, then releases the object and uncoils itself to return to its original configuration (Refer to the supporting video: S3-S5 for the complete demonstration). Fig. 9 shows the plots of applied magnetic field \((B_x, B_y)\), its orientation \((\theta_{act})\), position of the nitinol backbone \((P)\), the desired \((\theta_{des})\) and estimated \((\theta_{est})\) tip angles of the VSR during the experiment time \((t)\). The four stages of the experiment occur as follows: grasping phase \((t = 0–254 s)\); coiling action \((t = 255–296 s)\); uncoiling action \((t = 297–348 s)\); releasing phase \((t = 349–682 s)\).

The grasping force of VSR sample 2 is characterized at three coiling deformation angles of 360°, 270°, and 180°. The grasping forces at magnetic fields of 30 mT, 20 mT, and 15 mT are measured by the force sensor as the VSR is retracted by the linear stage. Fig. 10 shows the plots of the grasping force along \(-x\)-axis \((F)\) as a function of the linear displacement of the VSR \((D)\). It is inferred that the grasping force increases with increasing coiling deformation angle and with increasing magnetic field strength. A maximum grasping force of 1.45 N is obtained for a coiling deformation angle of 360° at a magnetic field of 30 mT.

V. DISCUSSIONS AND FUTURE WORK

In this letter, we have demonstrated a proof-of-concept of the grasping and releasing of various diameter cylinders using a variable stiffness magnetically-actuated continuum robot. In doing so we have addressed the non-trivial problem of controlling large
Although there are no theoretical issues with the consideration of the gravitational force, these simplifications were made on purely practical grounds. Any future study should look to both consider gravity and to control the VSR in unconstrained three dimensional space.

A further simplification worthy of mention pertains to the visual tracking algorithm. Our system locates the tip of the VSR and derives the tip angle to use as a control input. When the VSR wraps into a full circle the tip ceases to be visible, rendering this method of tracking impossible. Any further study should therefore encode a system for tracking the position and size of the circle after a certain deformation angle is achieved. Further ahead, and for a more clinically relevant demonstration, visual tracking is not possible inside the human body so some non-visual sensing method (e.g. medical imaging or strain sensing) should be incorporated.

The bending radius is an interesting parameter worthy of mention here. The radius of the circle around which the robot is magnetized has a profound impact on the achievable radii of the wrapped robot under actuation. If this bending radius is too small the elastic torque will overpower the magnetic torque and the robot will snap open. This can be mitigated to a limited degree with a larger applied field magnitude. Furthermore, if the retraction of the nitinol backbone is not correctly synchronized with the rotation of the applied magnetic field, the actuation descends into the imbalances shown in Fig. 5 and the supporting video. Consequentially, the timing of the retraction of the sliding nitinol backbone is a function of the bending radius (the magnetization) and is enabled by having sufficient magnitude of applied field.

The most obvious limitation of this design is that the backbone is always, when present, straight and the base upon which the VSR is mounted is static. As magnetic actuation is an inherently small scale technology with its most likely applications in minimally invasive surgery (and similar) these constraints limit the current clinical relevance of the design. In order to navigate to any area of interest we should be soft, compliant and mobile. These limitations are by no means definitive however, and the imminent next step is to develop miniaturizable backbones with variably compliant behavior. This would open the door to a truly generalizable grasping VSR. This, however, is non-trivial and one of the significant challenges to the conceptual development of this design. Potential solutions lie in the areas of fluidic actuation [40], phase changing materials [20], electro-statics [41], magneto-rheological fluid [21] and vacuum locking [42] and we intend to explore those options with sufficient potential for miniaturization. Further to this we must also develop a mobile mounting system, such as a manual endoscope, to operate.

We also anticipate developing more reliable and miniaturizable automated fabrication techniques. Although the lower size limit of this design is still an open question, this will allow us to shrink the prototype and potentially incorporate more complex and interesting variable stiffness features.

VI. Conclusion

This letter presents a proof-of-concept of a tongue-like, magnetic variable stiffness coiling robot. This system exploits
variable lengthwise mechanical properties to achieve high deformation equilibrium in a way which has not previously been shown. We have demonstrated a closed-loop control strategy to grasp and release objects of varying sizes by synchronizing the sliding nitinol backbone of the robot with the actuating magnetic field. With this contribution we have demonstrated the currently untapped potential of functionalizing variable stiffness magnetically-actuated robots for higher energy state deformations. The variable stiffness grasping robot has potential as a surgical tool for applications in cargo delivery and collection.

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