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Towards Bimanual Operation of Magnetically Actuated Surgical Instruments

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***Abstract*— Advances in magnetically actuated surgical instruments have reduced the size and increased the dexterity of tools for minimally invasive surgery. However, studies typically focus on evaluating the control of individual instruments during tool development, while few studies examined the deployment of multiple tools, despite the common need for bimanual operations in surgery. When more than one magnetically actuated instrument is positioned in close proximity and controlled with the same magnetic field source, uncoupled and independent control of multiple instruments becomes challenging due to the complex magnetic interactions from the magnetic instruments' interference and the external field actuation. The current paper proposes a novel bimanual operation approach, where one instrument is designed to be actuated using a spatially uniform magnetic field with static directions, and the other instrument is designed to be actuated with a rotating magnetic field. The proposed concept was evaluated with experiments and demonstrated with a simulated bimanual tissue cutting task, using an electromagnetic navigation system and two magnetic tools (a gripper and a pair of scissors) that satisfy the magnetic actuation design requirements. During bimanual operation, experiments showed a 19% gripping force drop of the gripper and less than 10% closing force drop of the scissors, resulting in 35 mN of scissors closing force for cutting.**

I. INTRODUCTION

The advancement of minimally invasive surgery (MIS) has significantly influenced modern surgical medicine, and it has greatly driven the evolution of novel surgical tool development. With the need for minimization of surgical traumas and miniaturization of surgical tools, robot-assisted MIS (RMIS) is often introduced to achieve tremor-filtered movements while being indefatigable [1]. With remote-control enabled, tele-operation can further expand the advantages of RMIS. One of the principal challenges faced by RMIS is regarding the size of instruments, rendering them unsuitable for micro-procedures that necessitate miniaturized instruments such as neurosurgery in which a tool is less than 2 mm in diameter. Recent advancements in magnetically actuated instruments provided a promising approach to downsizing the instrument for use in surgical settings with additional benefits such as wireless actuation [2], [3].

Utilizing magnetically actuated tools in surgical procedures requires both specially designed surgical instruments and a source of magnetic field, typically under the guidance of an imaging system [4]. To effectively control the magnetically driven instruments within the patient's body, it is necessary to create magnetic fields using permanent magnets [5]–[7] or electromagnetic (EM) coils [8]. While a single permanent magnet produces significant field gradients that create control challenges where a uniform field is needed, using two or more magnets enables the creation of a spatially uniform magnetic field [9]. However, using EM coils generates more homogeneous magnetic fields with a larger control space and offers increased potential for clinical applications, particularly in that the manipulation of the magnetic field necessitates no physical displacement of any component within the system [4], [10].

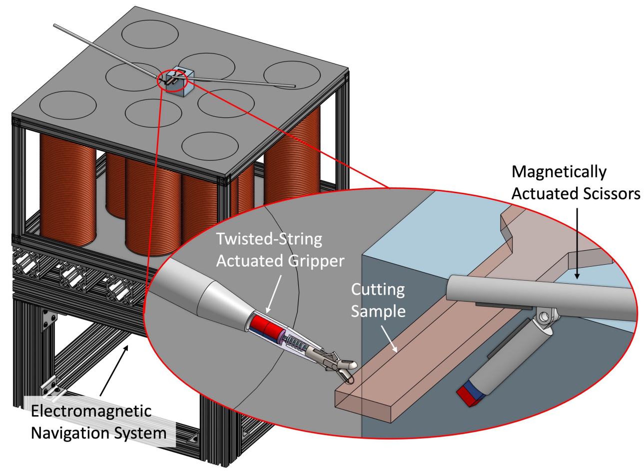

Fig. 1. Schematic of an example bimanual operation of magnetically actuated surgical instruments with an electromagnetic setup. While the gripper holds the hanging end of a cutting sample, the scissors can be actuated to cut.

From a practical standpoint, there is often a need for at least two instruments to work together for a specific surgical task (Fig. 1). However, placing multiple magnetically actuated instruments within the same magnetic field would lead to new challenges in the independent control of each instrument, and novel control methods are required. Selective and independent magnetic control has primarily been studied on the micro-scale untethered robots, where independent control of multiple magnetic microrobots can be achieved using strategies based on the spatial location of agents, heterogeneity between agents, or sophisticated magnetic field control [11], [12]. In surgical settings, multi-tool magnetic control has been explored using multiple local EM actuators [13]. Alternatively, tools can be designed with

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special geometry and magnetization directions [7]. However, there is a lack of scalability in these approaches, and this paper proposes a novel scalable approach that allows two tools, designed with different modes of magnetic actuation, to be operated using a single source of magnetic field generated by an EM setup.

The following sections provide details about two magnetically actuated instruments selected for evaluation and the EM setup employed. Experiments were conducted to evaluate the effectiveness of independent control of the two selected instruments. The feasibility of the proposed method was demonstrated with a simulated surgical cutting task requiring forceps to hold while the scissors cut the tissue sample. While magnetic interaction between the two tools is not considered in this work, we show that the effects can be avoided by keeping the tools adequately far apart.

II. DESIGN AND MODELLING

The emerging field of magnetosurgery employs magnetic force and torque to guide, actuate, and manipulate surgical tools [4]. Magnetic objects can be effectively modeled as a single-point magnetic dipole with a magnetic moment $\mathbf{m} = [m_x \quad m_y \quad m_z]^T$, assuming they are far enough from the source of the magnetic field. When a magnetic object with magnetic moment $\mathbf{m}$ is manipulated in a controlled magnetic field (with magnetic flux density $\mathbf{B} = [B_x \quad B_y \quad B_z]^T$), the magnetic force ($\mathbf{F}$) and torque ($\mathbf{T}$) that act upon the object can be modeled as

$$\mathbf{F} = \nabla(\mathbf{m} \cdot \mathbf{B}) = (\mathbf{m} \cdot \nabla)\mathbf{B} \tag{1}$$

$$\mathbf{T} = \mathbf{m} \times \mathbf{B}. \tag{2}$$

As all magnetic objects used here for instruments were hard permanent magnets, the $\mathbf{m}$ is assumed to be constant. When an external magnetic field is applied, the induced magnetic force would translate the object in the direction that would result in an increase in $\mathbf{m} \cdot \mathbf{B}$, and the induced magnetic torque would rotate the object in the direction that would align both $\mathbf{m}$ and $\mathbf{B}$ to the same direction [14].

For the proposed bimanual operation approach in this paper, only magnetic torque was utilized. Whenever a magnet is attached to a pivoting linkage, generating a magnetic field non-parallel to the magnet's magnetization direction creates a magnetic moment for actuation. On the other hand, instruments equipped with a cylindrical magnet, magnetized across its diameter, can be actuated with a rotating magnetic field, where the magnet would rotate to maintain alignment with the external magnetic field direction. Suppose two surgical instruments are designed to be actuated with the two types of magnetic fields, respectively. When the static magnetic field is generated with a direction perpendicular to the plane of rotation of the actuating field used by the other tool, the static magnetic field should not generate magnetic moment to the cylindrical magnet. This section first introduces the EM setup used to generate the magnetic field required, and the proposed bimanual operation is then further examined with two magnetically actuated surgical instruments, designed with the required modes of actuation.

A. Electromagnetic Navigation System

In this study, a previously developed eight-coil electromagnetic navigation system (EMNS) [15], as shown in Fig. 1, was used to generate the required magnetic field. Each coil of the EMNS consists of 10 layers of 163 turns of copper wire, with a cast iron core. Additionally, the entire device is supported by t-slotted aluminum framing with a flat tabletop designed for unobstructed surgical operations. The entire system has an overall estimated weight of 450 kg and can provide large workspace accessibility of up to 220°. To effectively control the orientation-independent five-DOF force and heading of a magnetic object, at least eight magnetic sources are required to generate an eight-DOF magnetic field [16]. For a system of n arbitrarily arranged EMs, the magnetic field $\mathbf{B}$, and its field gradient $\mathbf{G} = [\partial B_x/\partial x \quad \partial B_x/\partial y \quad \partial B_x/\partial z \quad \partial B_y/\partial y \quad \partial B_y/\partial z]^T$ at any point ($\mathbf{p}$) in the workspace can be linearly mapped to the applied currents $\mathbf{I} = [i_1 \quad i_2 \quad \dots \quad i_n]^T$:

$$\begin{bmatrix} \mathbf{B(p)} \\ \mathbf{G(p)} \end{bmatrix} = \mathbb{F}_I \mathbf{I}, \tag{3}$$

where $\mathbb{F}_I$ is a $8 \times n$ matrix. Such that, the k-th column of the $\mathbb{F}_I$ matrix represents the field and the field gradient at the given point $\mathbf{p}$ created by setting current i_k to 1 A and all other currents to 0 A [14]. However, when controlling the current input to the electromagnets, it is typically more practical to compute the inverse of the $\mathbb{F}_I$ matrix, such that the input current can be determined, given the desired magnetic field and gradient to be generated at point $\mathbf{p}$:

$$\mathbf{I} = \mathbb{F}_I^{-1} \begin{bmatrix} \mathbf{B}_{\text{des}}\mathbf{(p)} \\ \mathbf{G}_{\text{des}}\mathbf{(p)} \end{bmatrix}. \tag{4}$$

Practically, $\mathbb{F}_I^{-1}$ can be obtained by calibrating and testing with gaussmeters positioned in the workspace. This allows manipulation of the EMNS by controlling the current input, ensuring the desired magnetic flux density and gradients in all directions are specified. The utilized EMNS is capable of generating a magnetic field with a magnetic flux density of up to 45 mT at the center of its workspace.

B. Magnetically Actuated Surgical Instruments

Magnetically actuated tools with intended use in MIS typically miniaturize traditional surgical instruments, enabling smaller incisions and deeper reach. Within the confined spaces of the human body, they provide dexterity enhancement for effective manipulation. Moreover, magnetic actuation presents a favorable choice for wireless operations. For effective bimanual control of such tools, two instruments (a gripper and a pair of scissors as introduced in this section) were chosen based on both the surgical tasks that they were designed for and their modes of magnetic actuation.

1) Twisted-String Actuated (TSA) Gripper: It was first designed and prototyped by Nica et al. [17], and a further miniaturized version of the gripper was developed for this study. As shown in Fig. 2, when a rotating magnetic field $\mathbf{B}$ is externally applied, the neodymium iron boron (NdFeB) cylindrical tube magnet that is magnetized across its diameter

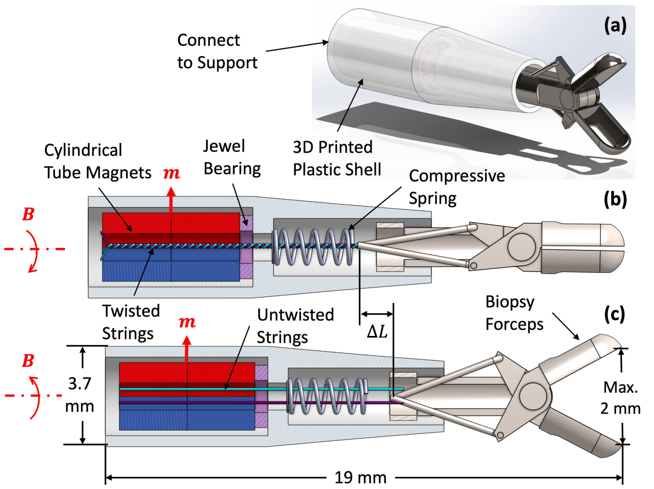

Fig. 2. **(a)** The assembled magnetically actuated TSA gripper design. The cross-sectional view of the design is presented with **(b)** forceps closed when the strings are twisted and **(c)** forceps opened when the strings are untwisted.

(with magnetization direction **m**), with two strands of string passing through its core, would rotate to align with the external magnetic field. Simultaneously, the tightened elastic string would be twisted, and the axial length of the twisted string would be shortened relative to the original length (with $\Delta L > 0$), thereby translating the rotational magnetic field to linear motion of the attached mechanism (i.e., the forceps). Mathematically, both the axial force generated by the twisted string and the input torque required to twist the string can be modeled as a function of the geometry and mechanical properties of the string, along with the initial length, angle of pre-twisting under minimal load, and angle of twisting during actuation of the string [17]. As the angle of twisting increases, the magnetic flux density must increase to overcome the torsional resisting torque.

For the gripper's designed operation, applying an external rotating magnetic field would rotate the cylindrical tube magnet, shorten the axial length of the twisted string, and close the biopsy forceps. With a larger number of rotations of the tube magnets, the forceps generate a greater gripping force. Through testing, it was also observed that, with the existence of friction, the forceps would not reopen with the twisted strings untwisted, unless a rotating magnetic field in the reversed direction is applied. Such that, a different magnetic field can be applied to other magnetically actuated tools without interfering with the TSA gripper, as long as the generated field does not closely follow the reversed rotating direction of the magnetic field that was used to close the forceps. This practical observation was critical to the successful operation of more than one magnetically actuated tool within the same magnetic field.

2) Magnetically Actuated Scissors: A pair of magnetically actuated scissors was previously designed and prototyped by Onaizah et al. [19] and then improved by Bao [18]. As illustrated in Fig. 3, the scissor design was made of titanium blades assembled within a 3D printed protective shell made of resin (ClearV4, Formlabs, USA), and a cubic

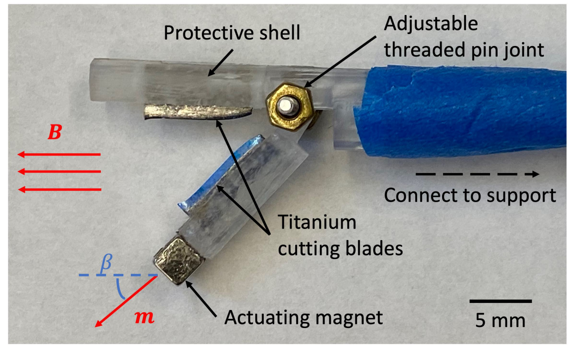

Fig. 3. Prototype magnetically actuated scissors in opened state, modified from [18].

NdFeB permanent magnet for actuation (with magnetic moment **m**) was glued at the tip of the shell. When a spatially uniform magnetic field **B** is applied in the direction of the scissor blades' opening, the magnetization direction of the magnet would attempt to align with the external field, driving one blade to close the scissors for cutting. Meanwhile, the larger the angle of blades opening ($0° \leq \beta \leq 90°$) and the magnetic flux density are, the greater the cutting torque can be achieved. Applying magnetic fields perpendicular to the scissor blades' opening would reverse the process.

C. Uncoupled Bimanual Operation

As mentioned above, we propose that the actuation of the scissors can theoretically be independent, without interfering with the gripper's stability, using the same magnetic field source. Particularly, when the gripper is closed, applying a spatially uniform magnetic field in any direction would only rotate the cylindrical magnet of the TSA gripper (i.e., untwist the twisted string) by at most half a cycle, where the magnet rotates to align with the external field direction. Meanwhile, rotating the gripper's magnet by half a cycle causes a insignificant change in its gripping force, as will be shown through experiments. The magnetic scissors can be operated within the same workspace without significantly reducing the gripping force of the TSA gripper. However, the TSA gripper cannot be controlled independently of the scissors. When a rotating magnetic field is applied, it is practically challenging to align the field's axis of rotation perfectly parallel to the scissors' blades opening. During experiments, any minor changes in the environment (e.g., vibration, field inhomogeneity) would actuate significant undesired closing and opening of the scissor blades.

III. EXPERIMENTS AND RESULTS

The proposal of bimanual operation of magnetically actuated tools in this work suggests that such operations can be achieved if the two instruments are designed to be actuated with two different modes of magnetic actuation (i.e., spatially uniform rotating and non-rotating magnetic field). To further evaluate the proposed concept, a set of experiments was conducted using the scissors and the gripper introduced in previous sections. Experimental results in this section are meant to provide a typical set of evaluations that would be required for the assessment of any bimanual operation of magnetically actuated tools. It should also be noted that the experimental results presented are tools dependent, and the achievement of bimanual operation can be expanded to other tools designed with similar modes of magnetic actuation.

A. Limits of Inter-Magnetic Forces

As both evaluated instruments are magnetically actuated with magnets onboard, positioning two instruments in close proximity inherently presents interacting magnetic forces between the tools. For the designed functions of the two surgical instruments used in this study, a safe range of operation was defined, such that placing the opened scissors close to a fixed gripper in space would not close the scissors undesirably, causing unintended damage to the patient. In 3D space, this safe range of operation would be approximately a sphere (or an ellipsoid given the magnet's length). In our study, it was found that friction in the scissors' pivot point would be sufficient to hold from closing the blades when the distance between the two magnets was greater than 15 mm.

B. Variation of Gripping Force during Operation

To achieve the proposed bimanual operation, minimizing the loss of gripping force during the actuation of the scissors was critical. Using the testing setup shown in Fig. 4(a), the change in gripping force during a simulated bimanual operation was quantitatively examined. The gripper was positioned to grip on a rigid connector to a fixed one-axis force load cell (LSB200, Futek, USA), such that the jaw's closing direction aligns to the load cell's loading axis. With results presented in Fig. 4(b), a simulated bimanual operation was carried out in five stages. Using the EMNS, a 20 mT rotating magnetic field with a rotating frequency of 1 Hz was first generated to actuate the gripper in stage (I) until the amount of gripping force peaked out. The rotating magnetic field was turned off when the cylindrical magnet slipped back one cycle to catch up with the next rotation of the magnetic field in stage (II), indicating the amount of twisting torque required exceeded the amount of magnetic torque generated. With the magnetic field turned off and the gripper at rest in stage (III), friction was in place to hold the magnet from untwisting the twisted string, where 3.6% of gripping force was lost in 3 seconds. Then, a spatially uniform magnetic field was momentarily generated in the y direction in stage (IV), and subsequently in the z direction in stage (V), to simulate the actuation of the scissors in the workspace. As shown in Fig. 4(b), actuating the scissors could result in both gains and drops of the gripping force, depending on the magnetization direction of the cylindrical magnet. In this particular test, 6.3% force gain and 19% force drop were recorded in stage (IV) and (V), respectively.

C. Variation of Cutting Force during Operation

Although the magnetic actuation of the scissors was controlled independently of the TSA gripper, the existence of the gripper's onboard magnet in the workspace creates a second source of magnetic field. Experiments were performed using

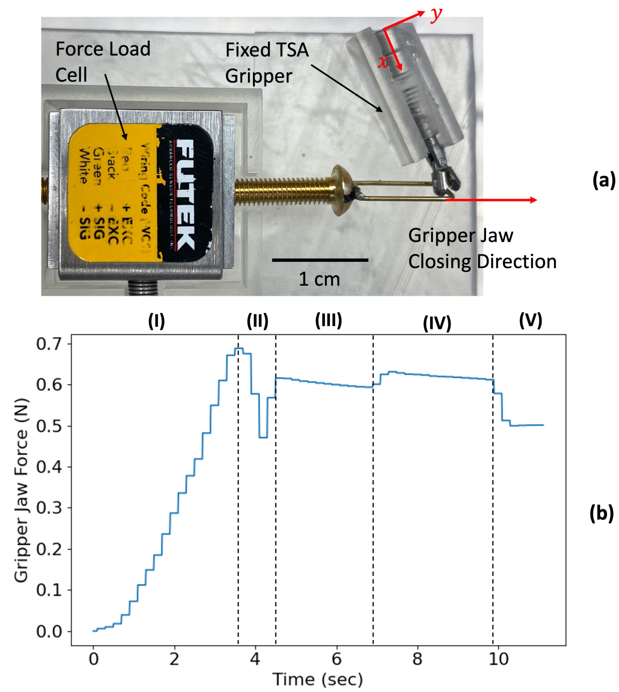

Fig. 4. (a) Force testing setup with the TSA gripper shell constrained from rotating in a 3D printed slot and jaw clamping on a rigid connection to the force load cell; reference frame of the EMNS was marked on the gripper. (b) The variation in gripping force was experimentally measured during a five-stages simulated bimanual operation. A rotating magnetic field about the x axis actuated the TSA mechanism in stage (I) until maximum gripping force reached and the magnet slipped for one cycle in stage (II). Minimal force loss was observed with magnetic field turned off in stage (III). Then, spatially uniform magnetic field was turned on momentarily in the y and the z axis in stage (IV) and (V), respectively, to simulate the actuation of the scissors and observe gains and drops of the gripper's jaw force.

a similar setup as in Fig. 4(a) to evaluate the closing force of the scissors when the TSA gripper was absent and positioned unactuated nearby in the workspace, where results are presented in Fig. 5. Forces were measured with the scissor blades opened at an angle of $58°$, and the centre-to-centre distance between the two instruments' onboard magnets was 20 mm. It was found that the magnetic effect of the gripper's cylindrical magnet on the scissors' cutting capability (i.e., torque generated to close the blades) was minimal to be below 10% loss in closing force for all tested field strengths from an experiment trial. This observation holds true only given that the scissors were not positioned inside the unsafe zone, where significant inter-magnetic interactions would take place even without an external field applied.

D. Vibration during Operation

When one instrument is actuated with the externally applied magnetic field, the magnetic interaction acted upon the other instrument in the workspace may cause undesired vibration. This is mostly caused by the magnetic torque generated when the angle between the field direction and the onboard magnet's magnetization direction is large. However, through experimental testing, it was found that reliable fixtures and connections for the delivered tools can effectively reduce vibration to a non-observable level during operation.

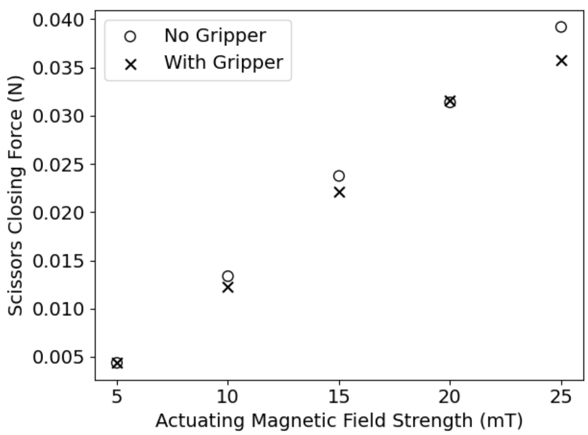

Fig. 5. Experimentally measured closing force of the scissors, actuated with and without the gripper positioned unactuated within the same workspace.

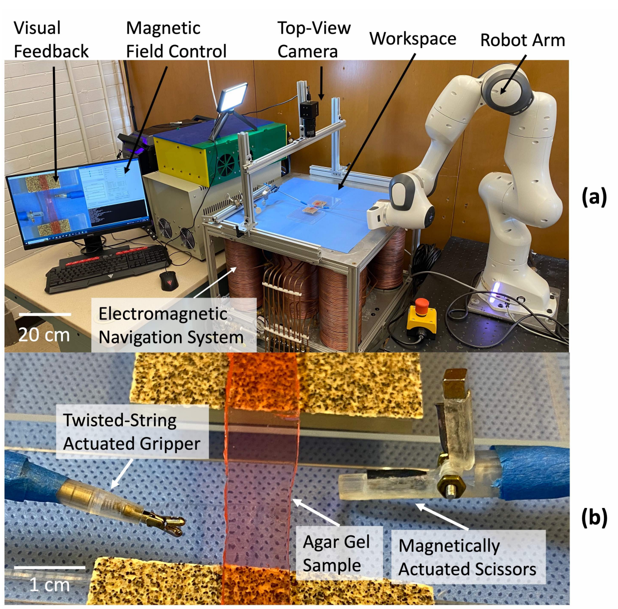

Fig. 6. Experimental bimanual task setup showing (a) overall and (b) closeup.

IV. DEMONSTRATION

To demonstrate the feasibility of the proposed bimanual operation of magnetically actuated tools for surgical applications, a demonstration with the setup shown in Fig. 6 was performed to simulate a surgical soft tissue cutting task using a gripper to hold the tissue for scissor cutting.

To simulate a surgical tissue cutting environment, a setup that was previously used to evaluate miniature surgical scissors was adopted [20]. Agar gel was prepared with a low concentration (1.5% by weight) of agar powder (AGR001, BioShop, Canada) to simulate the mechanical properties of brain tissue, given its ease of preparation [20]. During the experiment, both ends of the agar gel was supported on plastic platforms with sandpaper attached to avoid horizontal sliding. Both magnetically actuated tools were each connected through a glass rod to be delivered to the surgical site. Specifically, the scissors were attached to the end effector of an industrial robot arm (Franka Research 3, Franka Emika, Germany), and the gripper was secured by a three-fingers clamp. During operation, the positioning and trajectories of both tools were manually controlled. The generation of the applied magnetic field was achieved through open-loop current control of the EMNS, tele-operated through a customizable user interface with real-time visual feedback of the workspace enabled.

As shown in Fig. 6, a 1.5 mm thick slice of agar gel sampled was first positioned at the center of the EMNS workspace, where the magnetic field generation of the EMNS was calibrated at. The TSA gripper was first introduced to the surgical site manually and secured by the clamp. With the gripper positioned at the desired gripping position, a rotating magnetic field was applied to close the forceps and slightly lift the agar gel for cutting. Then, the magnetically actuated scissors were introduced to the cutting position through the robot arm, where a spatially uniform magnetic field with a specified direction was then applied to complete the cutting. The bimanual control of the two selected tools enabled a simulated operation to grip, hold, and then cut tissue from the surgical site. The procedure was repeated three times, and all samples were successfully gripped and cut through with two to three times of scissors actuation. Key frames of the supplementary video are presented in Fig. 7.

V. DISCUSSION

While we were able to achieve independent control of the scissors, independent control of the gripper was not possible when the scissors were also in the same workspace. Although the negligible loss of gripping force was observed when the scissors were actuated, it should be noted that there exists a limit in the number of turns the twisted string can be untwisted before a significant amount of gripping force would be lost. If the scissors were to be actuated multiple times, the TSA gripper may need to be re-actuated with the scissors first pulled away from the workspace, which would inevitably add to the total surgical time in practice. Further, the inter-magnetic interaction between instruments and the scale of the tools also limit the minimum open volume required at the surgical site for uncoupled operations.

Nevertheless, the current study warrants future work to be conducted. All surgical instruments in this paper were deployed with straight and rigid connections as an exploratory study, even if the tools were originally designed to be operated wirelessly. Future development towards MIS should also explore the connection to flexible and steerable robots for increased dexterity [3]. To further amplify the advantages of applying magnetically actuated instruments in MIS, future research should also explore the control of one or more untethered robots, which further miniaturize surgical tools for reduced invasiveness. However, it may also impose additional technical challenges, such as controlling the inter-robot magnetic force interaction, reducing undesired vibration during operation, and obtaining a source of visual feedback to provide an intuitive reference for the user.

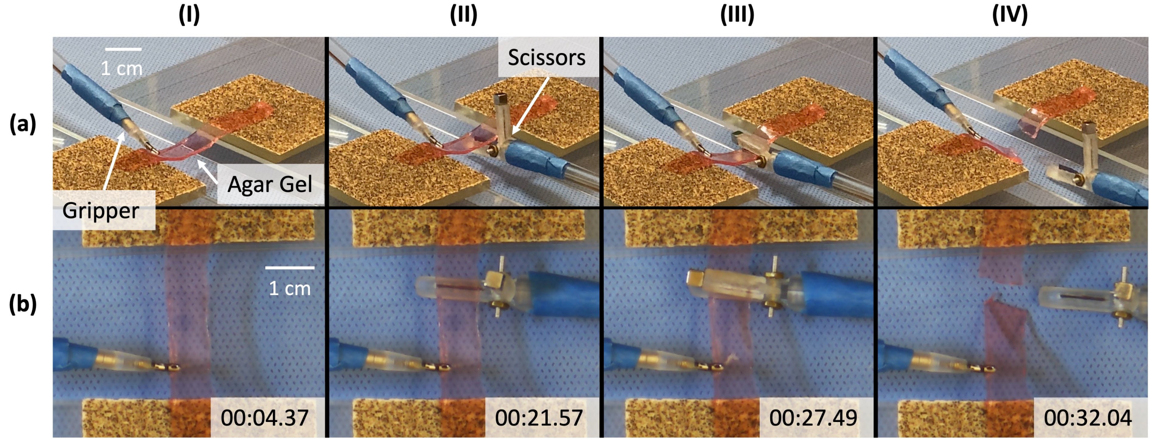

Fig. 7. The (a) side view and (b) top view of the demonstration on bimanual operation of magnetically actuated surgical instruments. (I) The gripper was first introduced and actuated with a rotating magnetic field to grip on the agar gel sample and hold it steady for subsequent cutting. (II) The scissors were then introduced, and (III) a spatially uniform magnetic field was generated in the direction of the scissors' blades opening to actuate cutting. (IV) The scissors were retrieved with the agar gel sample cut and gripper still holding the sample after two cutting attempts actuated.

Further, translating untethered magnetically actuated robots also requires the generation of magnetic gradients, which was not explored in this work.

Although only two specific tools were evaluated in this study, other tools with the same modes of magnetic actuation as examined in this study may also be compatible with the proposed bimanual control framework. Diversification of the magnetic actuation modes for future development of magnetically actuated surgical instruments should be encouraged. Depending on the designed application of the new tools, the existing set of evaluating experiments can be expanded. For instance, MIS typically couples with one or more forms of medical imaging techniques [4], but performing magnetic resonance imaging (MRI) during the operation may cause undesired magnetic interactions. During surgical procedures, especially in confined spaces with delicate structures such as the human brain, all tool movements need to be highly predictable with necessary safeguards designed. Future research should also explore the implementation of force feedback for enhanced closed-loop control.

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