Magnetic Surgical Instruments for Robotic Abdominal Surgery

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Abstract—This paper reviews the implementation of magnetic based approaches in surgical instruments for abdominal surgeries. As the abdominal surgical techniques advance towards minimising surgical trauma, surgical instruments are enhanced to support such objective through the exploration of magnetic based systems. With this design approach, the surgical devices are given the capabilities to be fully inserted intra-abdominally to achieve access to all abdominal quadrants, without the conventional rigid link connection with the external unit. The variety of intra-abdominal surgical devices are anchored, guided and actuated by external units, with power and torque transmitted across the abdominal wall through magnetic linkage. This addresses many constraints encountered by conventional laparoscopic tools, such as loss of triangulation, fulcrum effect and the loss / lack of dexterity for surgical tasks. Design requirements in the aspects of clinical considerations are also discussed to aid the successful development of magnetic surgical instruments.

I. INTRODUCTION

Surgical techniques and technologies have progressed significantly over the past decades with the aim of minimising trauma to the patients. Apart from resulting in less pain and faster recovery, the reduction of trauma also minimises the number and severity of incisions, wound size and blood loss, hence reducing the potential of surgical complications. This has been demonstrated through the trend of the technical and technological development of the surgical procedure: from open surgery to laparoscopic or minimally invasive surgery (MIS) [1], laparoendoscopic single site (LESS) [2], [3] and natural orifice transluminal endoscopic surgery (NOTES) [4].

The concept of decreasing surgical trauma via MIS [5], [6] (as shown in Fig. 1a), gained much popularity throughout the field of abdominal surgery since the 1990s, moving forward from the open surgical procedure. Since the first reported MIS procedure in 1988 [7], the benefits of MIS have been observed across a wide range of surgical disciplines. While MIS does not have the large workspace for surgeons to freely access different quadrants of the abdomen, it allows much smaller incisions, thus reducing the surgical trauma suffered by the patients. Furthermore, using relatively small incisions ranging

from 5mm to 12mm [8], this approach leads to less wound complications, less postoperative pain, shorter recovery period, better cosmetics, and earlier return to employment and daily activities, hence greater patient satisfaction [9]–[11]. More technical advantages of laparoscopy include lower likelihood of infections and blood loss, improving the preservation of normal immune function, thus lower morbidity rate [10], [12]–[14].

The persistent aim in minimising the invasiveness of surgical procedures stimulated further reduction in surgical trauma by introducing the LESS approach, as illustrated in Fig. 1b, with improvements in the aspects of cosmetics and recovery rate [15]–[17]. LESS aims to eliminate the need of multiple surgical incisions, utilising only one incision typically through the umbilicus [18], [19], for the insertion of laparoscopic surgical tools [20], [21]. Currently, LESS devices (e.g. SILS[TM] port, Triport[TM]) are widely available, with a plastic disk of 2 to 3 cm connected to a flange for multiple laparoscopic tools to be inserted through the umbilicus [22], [23].

Towards achieving the goal of a completely scarless surgery, NOTES has been proposed [24]–[27]. The NOTES procedures (see Fig. 1c) gain access to the abdominal cavity via various transluminal access (e.g. transgastric, transvaginal or transcolonic). Endoscopic-like surgical instruments are used to manoeuvre into the abdomen through an incision made in the stomach wall, uterus or colon to access the abdomen. Due to the cumbersome of procedural setup and manipulation with current available surgical instruments [28], [29] as well as the lack of cases to evaluate the possibility of infection [30], [31], NOTES remains largely experimental.

In all these approaches, it should be noted that the manoeuvrability of surgical instruments is constrained by the access port, which is created by surgical incision. This increases the complexity of multiple quadrants access in the abdomen. All these surgical methods were conventionally performed manually by surgeons with the use of rigid laparoscopic tools or endoscopic instruments, where limitations, such as human hand tremor, fatigue, inconvenient tools manipulation and limited vision of the surgical environment also added to the difficulties. The introduction of robotic surgical systems alleviated some of the shortcomings associated with the manual operation of the surgical instruments. Robotic MIS surgery, for example, is currently performed in over 3000 hospitals all over the world using the commercial Da Vinci platform from Intuitive Surgical [32]–[36]. The same company, which is the major player on the market (after the merger with its rival company, Computer Motion in 2003), recently released a new

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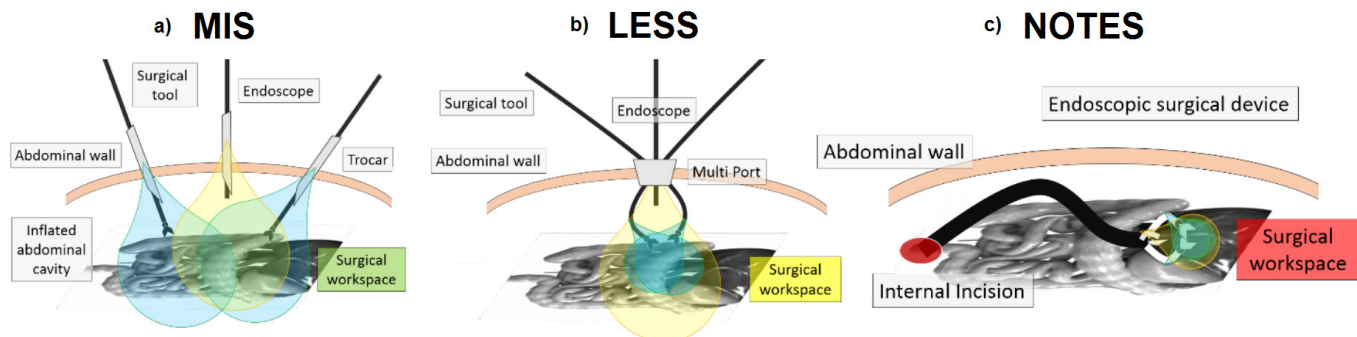
Fig. 1: Schematic representation of the abdominal surgery techniques. a) Minimally Invasive Surgery (MIS) scheme; each surgical tool requires a single port (trocar). b) Laparoendoscopic Single Site Surgery (LESS) scheme; mirrored surgical tool are used to fit a 2-3 cm multi-port. c) Transcolonic Natural Orifice Transluminal Endoscopic Surgery (NOTES) scheme; endoscopic surgical tool reaches the abdominal cavity though an internal incision.

system for MIS surgery, i.e. the DaVinci Xi [37]. DaVinci Xi has the capability to reach all the abdominal quadrants and 6 or 7 degrees-of-freedom (DOFs) at the end effectors thanks to its cable driven mechanism. Robotic LESS surgery is also explored through a platform that has recently obtained FDA approval, which is the Da Vinci Sp. The Sp platform consists of a single cannula that allows the deployment of three snake-like robotic arms and a stereoscopic vision head into the abdominal cavity. In contrast to the previous version, the DaVinci Single Site, the Da Vinci Sp offers more DOFs per surgical instrument, improving triangulation, tools congestion avoidance and multi-port dislodgement. Commercial robotic platforms for NOTES are yet to be available for clinical use. The complicated trajectory and the need for highly manoeuvrable and miniaturised robotic manipulators with the capability of endoscopic instruments limit the development of robotic platforms. The main technical challenges arise from the connection with long body devices that could deprive the instrument of the rigidity required by surgical tasks. Furthermore, the power available at the end effector is not always sufficient due to the required miniaturisation. A snake-like surgical endoscopic robot, the Flex®Robotic System by Medrobotics [38] that have just recently obtained FDA clearance for transoral surgery could bring future implementation of surgical robotics closer to NOTES as an inner snake-like body greatly caters for the rigidity in supporting the forces at the end effector.

Despite these advances, including those brought about by robotic surgery, challenges arising from having to perform surgery through small access port(s) remain. In all these cases, it has been noted that having to perform task manipulation using instrumentation constrained in its motion to have to pass through the small access ports contributes significantly to the challenges. Investigation into the possibility of removing such rigid body constraints was pioneered by Tillander *et al* [39], Yodh *et al* [40] and Montgomery *et al* [41], where magnets were used to replace rigid mechanical transmission. In these studies, significant advantages in the form of improved manipulability and mobility, while maintaining the level of minimally invasive access offered by other approaches, were demonstrated. Magnetic linkages, replacing rigid body

linkages, eliminates the need for the surgical instruments to maintain contact with the access port once inserted into the abdominal cavity. Multiple DOFs can be realised through the use of localised magnetic coupling, thus allowing dexterous manipulation. Magnetic anchoring allows mobility of such platform, providing access to multiple quadrants in the abdomen. Another potential advantage can be seen in the ability to transmit a large amount of power through the magnetic linkages without compromising the size of the instrument inserted into the body, thus suitable for miniaturisation.

In this paper, the emerging magnetic-based surgical techniques and technologies are reviewed, investigating the development of ideas, the challenges, the current state of the art and the promising potential in future surgical procedures. The reminder of this paper is organised as follows. Section II overviews the application of magnetism in the current abdominal surgery approaches. Section III reviews the implementation of magnetic coupling across the abdominal barrier for anchoring and guidance of surgical tools, both by manual operation and with onboard actuation embedded in the intraabdominal tool. The advancements into surgical devices with robotic control of magnetic actuation via the means of local magnetic and electromagnetic actuations are discussed in Section IV, with some insights on the surgical devices employing this strategy. Finally, in the process of developing effective magnetic-based surgical instruments, the technical and clinical considerations are summarised in Section V.

II. Magnetic-based Approach in Abdominal Surgery

Robotic assistance in MIS, LESS and NOTES thus far has extended the capabilities of surgeons via improved precision, dexterity, and computer assistance. The surgical approaches described in the previous section impose strict requirements on the design of surgical tools in terms of miniaturisation, dexterity and collision avoidance between surgical tools. Dexterity, proportional to the number of DOFs available at the instrument, decreases from open surgery to MIS, LESS and NOTES. The same trend is true for triangulation, defined as the capability to manipulate instrument smoothly along with

adequate visualisation during surgery, which decreases along with invasiveness decrease.

A promising approach that can improve both triangulation and dexterity for surgical instruments leverages the magnetic field interactions of two sets of magnets, located on the opposite sides of the abdominal wall. In this paper, sets of magnet located on the outside and the inside of the abdominal wall are referred to as the external unit and the internal unit, respectively. The interaction forces allow the transmission of torques across a physical barrier, and hence the transfer of mechanical power from an external set of driving magnet to the driven magnet embedded into the surgical tool, which is operating inside the human body.

The use of magnets in abdominal surgery was first reported by the successful utilisation of magnetic systems almost 65 years ago in neurosurgery and cardiology in guiding catheter tips through vessels. The very first magnetic guidance of intravascular catheter was experimentally evaluated in 1949 and published in 1951 by Tillander *et al* [42]. The device consisted of a catheter with an articulated steel tip that was steered by a magnetic field generated by a large electromagnet placed beneath a nonmagnetic surgical table. The advancement in technology and the possibility to regulate magnetic fields led to the translation to clinical use, such as Stereotaxis [43], [44] and Magnetecs [45], with the Stereotaxis obtaining FDA approval for atrial flutter treatment in 2010 [46].

In recent years, more magnetic-based medical devices received increasing attention, such as the capsule endoscopes (CE) for diagnosis and treatment of the gastro-intestinal (GI) tract [47], [48], with various designs exploiting magnetic-based navigation in colonoscopy [49]–[57], gastroscopy [58]–[61], tissue biopsy [54], controllable drug delivery [62] and tumour detection [63], [64]. Since then, the use of magnetic systems to deploy, place and drive independent surgical units intra-abdominally across the abdominal wall has tremendously intrigued researchers. This created an innovative class of externally actuated surgical instruments which can potentially improve triangulation and tool repositioning and lower surgical invasiveness.

III. MAGNETIC ANCHORING AND GUIDANCE SYSTEM (MAGS)

The Magnetic Anchoring and Guidance Systems (MAGS), introduced by Cadeddu and his team in 2007 [65], are surgical tools that benefit from magnetic anchoring between an external permanent magnet (PM) and an internal PM embedded in the internal surgical device. The anchoring serves to guide and reposition the surgical device through manipulation from the outside of the body. The attraction force acting on the internal PM anchors the internal device onto the inside of the abdominal wall. If the external PM is displaced along the surface of the abdominal wall, the magnetic misalignment generates a net force that will act on the internal magnet in the same direction as the displacement resulting in the internal device undergoing the same displacement. By having the magnetic poles of each magnet in parallel to each other, as shown in Fig. 2a, the translation and angular displacement

can be achieved, resulting in 3 DOFs of motion, i.e. translation along x and y and rotation about z (the yaw DOF).

A. MAGS with manual guidance

MAGS was investigated for its ability to perform simple surgical tasks [66], to manipulate a surgical camera [65], surgical retractors [65] and surgical cauterizer [67]. Different cameras have been proposed by the same group of authors (Cadeddu *et al*), where the latest version had Ethicon Endo Sugery involved in its development and was tested in clinical trials [65]. It consists of an illumination and vision system embedded in a wired capsule that contains a permanent magnet. The external magnetic handle is hand operated and gives the surgeon the ability to change the field of view of the camera in the internal unit by manually pressing the external PM onto the inflated abdominal cavity. Swain *et al* [68] studied the possibility to obtain a "stadium view" with a miniaturised (15 mm diameter and 30 mm length) camera and illumination systems attached to the abdominal wall. Trials highlighted the benefits of having a mobile camera hanging from the abdominal wall compared to the use of conventional endoscopes which suffer from tunnel vision, i.e. misperception of the surgical workspace for surgeons.

Surgical retractors in MAGS were designed with manipulation capability. Two external PM anchors are arranged such that its relative distance can be varied [66], resulting in the actuation of a device functional unit through simple mechanism (see Fig. 2b). A fan shaped end effector has been successfully used to retract liver portions in a porcine model. Further development on magnetic based retractor was made by Dominquez *et al* [69] and Cho *et al* [70], who developed a simpler but functional surgical retractor used in actual abdominal surgeries. Dominguez *et al* proposed a surgical grasper directly attached to a permanent magnet, while Cho *et al* tested a magnet-fixed endoscopic clip. The clip was manipulated by the surgeons using conventional surgical tools. Once attached to the point of interest, the clip was retracted by the magnetic attraction of the external PM.

From the *in vivo* experiments [67], [71], the potential of MAGS was validated as a technology that emphasises the aspects of self-anchoring capability, instrument guidance within the abdominal cavity and thus decreased invasiveness. However, without the capability to manipulate objects, only relatively simple surgical tasks have been demonstrated with these instruments thus far.

At this point of the development, it was desired to develop the capabilities already demonstrated through MAGS towards realising instruments that can perform more articulated surgical tasks within the abdominal cavity. Some amount of mechanical movements have been shown successful with the use of additional magnetic coupling for motion and actuation, however, they were found to be less dexterous and non-repeatable [66]. Similarly, Swain *et al* [60] attempted to hand navigate a Pillcam[TM] attached to a magnetic body deployed inside the stomach in human trials. The magnets are non-intuitive to operate as magnetic forces decays exponentially with distance. Hence, the hand operation of magnetically anchored devices
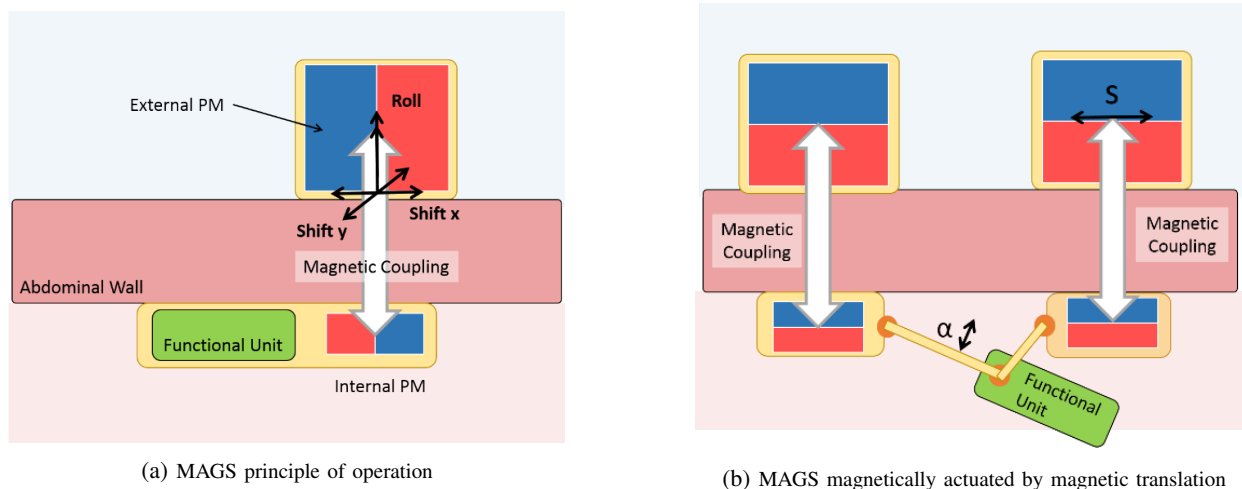
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(a) MAGS principle of operation

(b) MAGS magnetically actuated by magnetic translation

Fig. 2: Illustration of Magnetic Anchoring and Guidance System (MAGS)

was found to be non-reliable in a surgical scenario. For more reliable and accurate instrument manipulation, the concept of the simple magnetic attraction has to be further capitalised to adapt to more complex surgical tasks and motions.

B. MAGS with onboard conventional actuation

The ideas of incorporating on board actuation units onto MAGS surgical devices grew out of the need to enhance the manipulation capability of the instruments by decoupling the actuation for manipulation from the anchoring tasks. In this case, the MAGS instruments are further enhanced with on board actuators (e.g. miniaturised electrical DC motors) to drive a surgical instrument with higher number of DOFs mounted on the internal unit, for tasks requiring more dexterous manipulation within abdominal cavity (see Fig. 3).

A magnetically anchored and actuated device was first reported in [66] in the form of a three DOFs robotic cauteriser

Fig. 3: Operation principle of MAGS with on board conventional actuation

(introduced in subsection III-A). The surgical cauteriser, 158 mm long, is pneumatically actuated and embedded with permanent magnets at the instrument base for its anchoring. The pneumatic actuation did not guarantee a smooth operation of the device *in vivo*, but was able to generate sufficient force to elevate tissue and perform incisions on it. The performance of the device in terms of available force at the end effector and attraction forces at the instrument base, was not quantified by the authors.

Vision (camera) systems in surgical instrumentation do not generally require much mechanical power, defined as the product of force and velocity or torque and speed, as no tissue manipulation is required. However, a precise motion in different directions is necessary. In 2009, a camera system with controllable orientation (pan and tilt) and zoom for MIS surgery was proposed [72], incorporating the concept of MAGS enhanced with conventional motors. Two DC electrical motors connected with miniaturised gears provided the actuation for the two orientation DOFs while a third motor was used to linearly actuate the camera head thus resulting in zoom feature. The device, 9 mm in diameter, was designed without an anchoring solution and *in vivo* trials were performed by suturing the device onto the abdominal wall. The study however highlighted the potential use of magnetic links as a way to reposition and dock the device.

Another camera system, developed in 2012 by Terry *et al* [73], is an example of a magnetically anchored system with conventional actuation for the camera. The device designed for LESS surgery takes advantage of the larger port size (larger than that for MIS approaches) to embed the actuation and gearing systems for the camera motion on board the internal device. Three DC motors were used to provide the actuation to the two rotational DOFs (pan and tilt) and the translation DOF to change the camera relative position to the entry port and thus enhance triangulation. *In vivo* testing had shown an improvement in surgeon tasks completion due to the reduced instrument congestion compared to the the multi-port
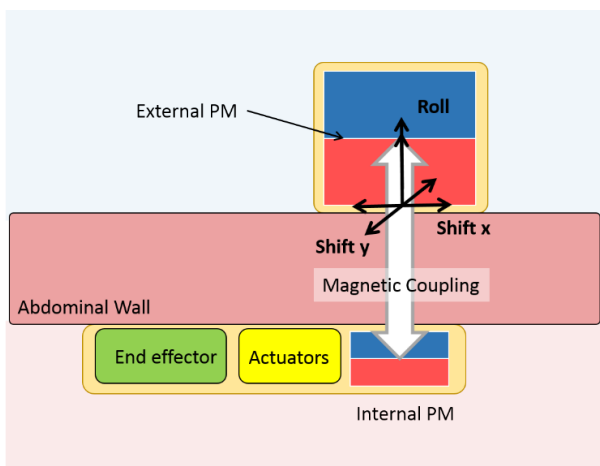
approach.

A magnetic surgical retractor has to be designed to support the device weight as well as the retracted load / tissue. A magnetic retraction device for NOTES was proposed by Oleynikov et al. [33] and consists of a MAGS platform that embeds two PMs and an electrical motor that bundle or unbundle a wired surgical clip. No description was given of the performance of the retraction system but the authors reported that limited simple manoeuvres were achieved. Tortora *et al* [74] developed a surgical retractor that consist of a retracting arm with two DOFs connected to a magnetic frame for anchoring purposes. The device utilises one DC motor to change the angular position of the retracting arm while the second motor is used to operate the end effector gripper. While sufficient grasping force is achieved at the end effector (5.3 N), the retracting force generated by the motor at the end effector is insufficient for surgical practice (1.53 N). The actuation torque in this case is already leveraged mechanically for the purpose of tissue retraction. The low power of electrical DC micromotors limits their applicability for surgical tasks that demands high power. In [74] the performance of the whole platform is also evaluated on a mock up simulator, consisting of a foldable triangular frame that embeds the PMs for anchoring with different instruments connected to it. The instruments include a four DOF robotic cauteriser, a four DOF robotic manipulators, a two DOF camera and a two DOF surgical retractor. The main benefits of connecting different instruments to the magnetic frame are that (1) the anchoring frame can embed bigger permanent magnets and support larger load and (2) the fixed position of the common base of the instruments improves triangulation, avoids instrument reciprocal interference and provides a known relative location between different instruments. However, the force available at the four DOF robotic tools tip, based on the same modular components, was not sufficient for further investigation in surgical practice (0.65 N).

In parallel, another 3-link miniature surgical robot for NOTES was taken into the *in vivo* non-survival porcine test beds by Lehman *et al* [75]. The robot consists of a central body with stereoscopic vision and PMs for the device anchoring. Attached to it, two arms with three DOFs, each attached and actuated by DC electric motors. The experimental validation demonstrated the possibility of combining magnets with traditional actuators for miniature robotic platform for surgery but the dexterity is found to be lower than using conventional platform (conventional MIS with non-magnetic based approach). To overcome the dexterity limitation encountered by this study, the same group developed a similar device with four DOFs per arm but without magnetic anchors [76]. The final dimension of the device could not allow transgastric deployment of the device; as a 20 cm opening on the abdominal wall was required. This platform is currently being developed for clinical used by Virtual Incision Corp [77].

Though the attempts to incorporate actuation capability in MAGS surgical devices using conventional motors for more dexterous manipulation are proven to be feasible for small payloads, the motors with sizes small enough to fit through the incision do not generally provide enough torque and payload capabilities for the surgical instrument manipulation.
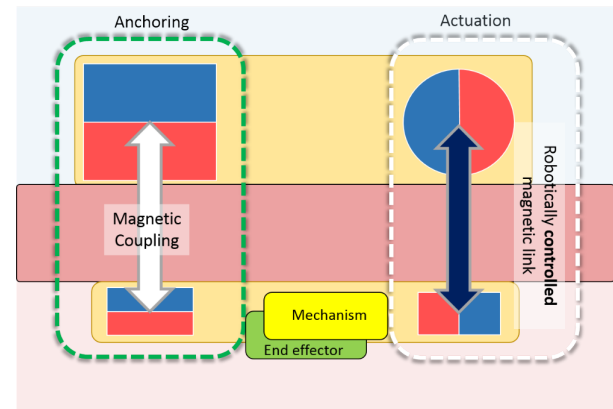

Fig. 4: Illustration of MAGS with robotic actuation

Nevertheless, the promising advantages of magnetic coupling were demonstrated in guiding and anchoring of surgical instruments, with now more complex robotic features, albeit limited in power. Surgical devices can be driven without direct connections between the internal unit and the external actuation. As such, surgical devices with embedded permanent magnets can be manipulated across the physical barrier of the abdominal wall through the appropriate manipulation of the magnetic linkages.

IV. ROBOTIC CONTROL OF MAGNETIC ACTUATION OF SURGICAL DEVICES

The following type of devices take advantage of the use of magnetic field to develop a generation of surgical devices with improved dexterity, reliable operation and more powerful actuation. Mechanical power can be transmitted through a magnetic linkage. The magnetic linkage can in fact be used statically to generate attractive forces for anchoring and guidance or dynamically to produce forces/torque in the internal device, as shown in Fig. 4. The resulting internal device is tether-less, and potentially with no electronics on board.

A. Magnetic actuation solutions

Various magnetic actuation solutions have been investigated for the cases where the absence of rigid link between the surgical tool and the actuation mechanism can improve the outcome for the patients. In the following, different magnetic links for actuation purposes are reviewed.

1) **Position control of permanent magnet** Using robotic control of the position and orientation of a permanent magnet, it is possible to regulate the amount of force and torque transmitted in a more reliable and repeatable manner than that performed manually. A medical field where this approach is well investigated is Capsule Endoscopy [78]–[81]. Challenges remain in the field in the effective localisation method for the location of the capsule relative to a known reference coordinate system required to close the control loop. In abdominal surgery there is less emphasis to localise the surgical instrument

since generally a camera system is used as a visual feedback to the surgeon performing the operation.

2) **Permanent magnets with shielding material** Brewer et al. [82] investigated the possibility of modulating the magnetic field by interposing magnetic shielding material between the external PM and the PM on board the internal device. By controlling the shield position and thus interaction-mitigation of the magnetic field, it is possible to have the force control over the internal device containing an on board PM. Moreover, an interesting result was reported for possible force regulation strategy: the amount of force transmitted to the device becomes linearly dependent on the shielding position.

3) **Electromagnetic coils** Coil is another magnetic field generator that has been used by Kummer *et al.* [83] to actuate and control the position of a miniaturised swimming robot for eye surgery. The magnetic field of a coil can be modulated as a function of the current running through the coil. Moreover, using multiple coils, it is possible to shape the magnetic field in determined areas.

4) **Servo control of rotating magnets** Diametrically magnetised cylindrical magnets can act like mechanical spur gears. The number of the magnetic poles is analogous to the equivalent number of teeth of a gear, while allowing contactless torque and speed transmission. Due to this feature, the magnetic coupling can be referred as magnetic gear [84]. A motor connected to such magnet can transmit power to another PM across a physical barrier to another magnet. This concept leads to interesting applications in the design of surgical devices reviewed in the following section.

B. Local magnetic and electromagnetic actuation

Local Magnetic Actuation (LMA) is a method for actuating surgical instruments based on the magnetic gear principle. In addition to the magnetic gear principle, LMA surgical instruments also take advantage of magnetic attraction force for anchoring and guidance, as elaborated in MAGS.

In the magnetic gear coupling, the motor is used to drive a cylindrical PM placed external to the body of the patient. Multiple magnetic gears can be used to actuate an equivalent number of DOFs for robotic surgical devices. An LMA magnetic gear unit was controlled with different closed-loop strategies by Di Natali *et al.* [85]. In this study, it is reported that with the selected PMs, it is possible to deliver an amount of power to the internal PM that is higher than that of a DC micromotor directly embedded in the internal tools. This addresses the main limitation of the traditional actuation techniques based on embedded DC motors on board the internal device.

The efficiency of the transmission however decreases with the increase of the separation distance between the driving (external) PM and driven (internal) one, associated with an increase in the abdominal wall thickness. This is due to the inverse exponential relationship the magnetic field has with the
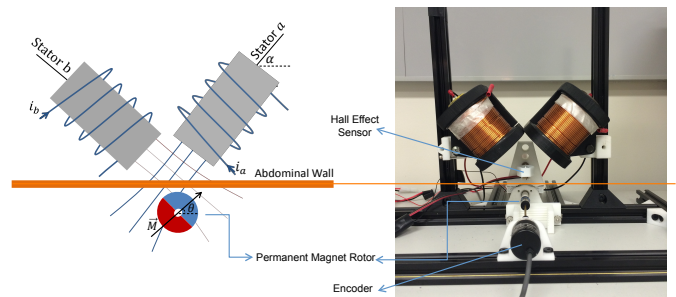

Fig. 5: Electromagnet coils replacing permanent magnets in the external actuation unit for higher level control in LEMA [86]

thickness of the abdominal wall separating the driving magnets and the load. It was also observed that pole slipping could exist between the external and internal driving magnets, reducing the amount of transferred torque significantly. Misalignment of the rotational axes of two permanents magnets was also reported as an issue [85]. To account for these limitations, Local Electromagnetic Actuation (LEMA) has been proposed [86], [87] whereby the external permanent magnets in LMA are replaced by electromagnets to generate a rotating magnetic field that produces moments to rotate the internal PM. The use of electromagnetic coils allows the modulation of the intensity of the magnetic field and thus providing a variable parameter which can be controlled to improve the performance of the system. The external electromagnetic coils can be thought of as being analogous to the stator of a DC motor while the driven internal PM as the rotor. In the case of large stator-rotor distance or high load torque, the magnitude of currents in the stators can be increased to compensate for the reduction of torque in permanent magnet inside the abdominal wall. Additionally, the ability to vary the actuation command to the electromagnetic stators would allow the implementation of a controller to compensate for mechanical uncertainties and inaccuracies, such as variable thickness and the misalignment of rotational axes [87]. In the reported design, two sets of electromagnetic windings were used as the stators to generate the magnetic fields to one (internal) rotor. This is required to avoid the ambiguity in the direction of resulting rotor rotation given the generated magnetic field. Additionally, the amount of current to each stator winding can be regulated independently, allowing more DOFs in the control for the resulting magnetic field, which in turn allow the system to compensate for the uncertainties.

A similar example based on rotating magnetic field to transmit torque to a driven magnetic body has been implemented by Dupont *et al* [88]. Using an MRI machine, a rotating magnetic field spins the ferromagnetic body connected to a plastic gear train which converts the rotary motion into a linear motion for actuating a needle insertion in neurosurgical settings. This technique produces one "global" magnetic field through the MRI machine that floods across the entire workspace (i.e. the entire person in the MRI). This is in contrast to the "local" method employed by the LMA (Local Magnetic Actuation) and LEMA techniques where the magnetic field is as much

as possible kept isolated between the driving external magnet and its intended pair of the driven internal magnet across the abdominal wall, thus allowing multiple magnetic couplings to be utilised to produce independent actuation over multiple DOFs.

C. LMA-based surgical devices

Motivated by the different robotic control strategies of magnetic field, researchers have already developed some promising device prototypes. Liu and his team [89] studied the optimal design parameters for a surgical camera system based on coil current control. Three electromagnetic coils shape the magnetic field and are used to actuate and anchor a capsule shaped camera with wireless communication for video streaming (Fig. 6). The capsule device embeds multiple magnets with different magnetisation on a hemispherical rotor at the capsule base. The device is yet to be fabricated and tested, but the proposed design can easily be integrated in commercially available vision systems such as Pillcam^{TM} or similar commercial platforms. Moreover, the proposed solution allows the anchoring and actuation functions to fuse into a unique magnetic link.

Another camera system based on controlled PM position has been proposed by Simi et al. [90]. With reliable motion and the fine-tuning of one of the DOFs used to change the field of view, the device can be used for LESS scenario. The proposed instrument has one body that contains the anchoring PMs, a flexible joint and a head containing a PM whose angular position is controlled by a DC motor, and a camera-illumination module (Fig. 7). By gradually rotating the PM in the head link, the forces acting on the head changes. The repulsion or attraction force, generated by the magnetic interaction with the corresponding external permanent magnet, is regulated by the rotation generated by the internal motor. The transmitted forces are thus responsible for the deflection of the flexible joint resulting in a change of viewing (angular) position. Bench test demonstrated the reliability of the tilt angle control. A maximum angle of 82 degree is achieved when the magnets are in maximum repulsive state. The dimensions of the device (i.e. 12.7 mm diameter and 120 mm in length) limit its *in vivo*
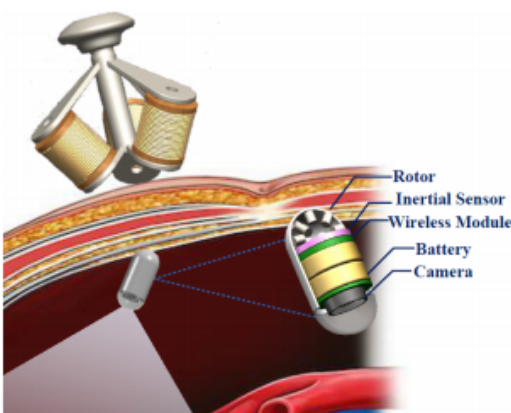

Fig. 6: Knoxville camera with external electromagnetic coils for intra-abdominal capsule actuation [89]
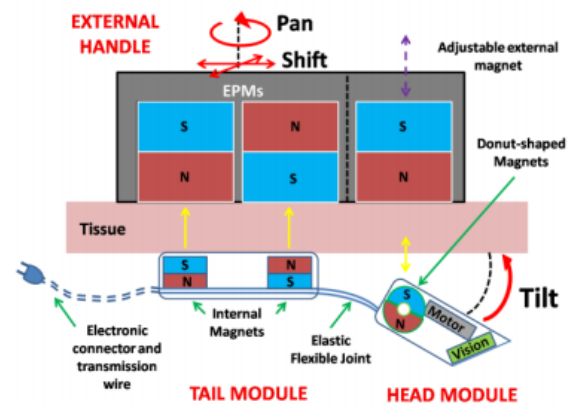

Fig. 7: LMA laparoscopic camera with fine tuning capabilities by Simi *et al* [90]

guidance, but the actuation principle allows a better exploration of the surgical field as well as optimal positioning.

The first LMA-based device is a surgical retractor developed by Garbin *et al* [91]. The magnetic gear allows the transfer of mechanical power in term of torque and speed to the internal PM from the external magnetic source (Fig. 8). An internal mechanical gearbox attached amplifies the torque available for actuating a retracting lever. Bench test were used to evaluate the device capability in terms of its retracting performance at varying abdominal wall thicknesses. A load of 500 grams was lifted with a 2 cm separation distance between the retractor and the external handle. The anchoring unit was observed to be the limiting component for the device in obese patients (abdominal thickness over 4 cm). When the separation distance is 4 cm, the device was found to only be able to lift 100 grams. The device, tested in porcine model, was able to successfully retract liver portions but demonstrated difficulties in repositioning due to its final dimensions (12.5 mm diameter and 120 mm long).

Driven by the possibility to deliver more power on board an internal surgical device through the LMA approach, Di Natali *et al* [92] designed a surgical manipulator with four DOFs. The device, combines two modules (as shown in Fig. 9). The left module consists of three magnetic gear coupled to the external powered units to actuate three rotational joints articulating the end effector. The right side consists of the robotic manipulator and its anchoring units, where their relative position is used to actuate the fourth DOF. This prototype is mechanically tested to be functional.

Robotic magnetic field control has the potential to improve the magnetic-based surgical tools given the possibility to implement different control strategies. Controlling the PM position in LMA approach allows precise and reliable movements. Servo control of rotating external permanent magnets provides higher torque to the internal permanent magnet in comparison to embedding electrical DC micromotors in the internal actuation unit. Electromagnetic coils have been explored in the LEMA variation of the approach, providing the ability to vary the magnetic field shape and strength when creating moment across the internal rotor.
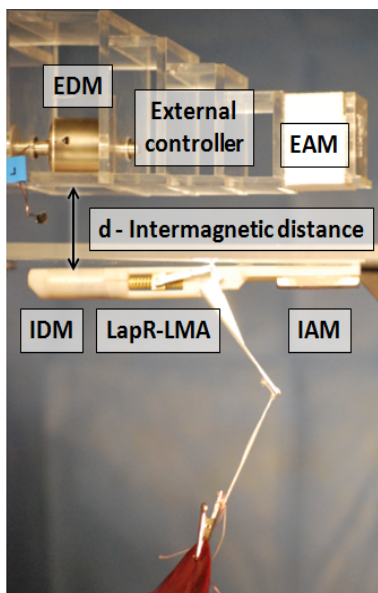
Fig. 8: LMA-based laparoscopic tissue retractor by Garbin *et al* [91]

V. Design considerations for magnetic surgical instruments

In order to develop effective and efficient surgical instruments, it is essential to take into the considerations the surgical environment involved. Furthermore, it is also vital to consider the methods and tools for the design of magnetic surgical instruments given the many technical challenges that magnetic systems are subject to.

A. Technical challenges and considerations

The interaction of magnetic fields are inherently nonlinear and complex, hence rigorous studies are required to ensure the feasible integration of magnetic systems into various applications. Such knowledge is important for the design, analysis and control development stages of the medical devices. Some fundamental models, such as the magnetic-pole [93] and the

Fig. 9: LMA-based surgical manipulator by Di Natali *et al* [92]

atomic current [94] modelling approaches have been widely used to design permanent magnets for diverse applications. To further extend the design analysis, the dynamic modelling of magnetic forces and torques is required for a system to function effectively [85], [95]. The results of the modelling and analysis play an important role in the design of the magnetic surgical platform to simulate and foreseen the actual surgical tasks requirements.

Actuator Options and Sizing The physical design of magnetic surgical instruments depends significantly on the type of magnetic systems required for the surgical applications, i.e. anchoring, guidance, positioning and manipulation. PMs are usually considered for anchoring and guidance due to their simplicity as the magnetic field coupling and interaction of the external and internal magnets are only required for static or quasi-static. For higher attraction force, squared PMs are recommended over the cylindrical PMs [96]. For more complicated tasks that require a varying magnetic actuation, the electromagnetic-based surgical platform combining PM anchoring is considered, with external electromagnetic coils employed to actuate intra-abdominal surgical tools through magnetic coupling with the internal magnets. The design of electromagnetic actuation in the surgical platforms depends on the coil dimension and parameters of windings and magnet core. In order to effectively control the external electromagnetic actuator to produce required force and torque during surgical manipulations, a variation of current flow through the coil wire is desired. The thickness of coil wires becomes a vital parameter to consider. The smaller the wire diameter, the higher the wire resistance, thus generating more heat as current passes through the wire. As a result, a cooling system would need to be incorporated to help dissipate heat from the system. This will result in an undesirable increase of platform dimension. The strength of an electromagnet also depends on the magnetic permeability of the core material. The higher the permeability of the core material, the better the magnetic field generation. Therefore, it is important to find a good match between a core with high permeability and thickness of the coil wires for efficient power transmission.

Design and Modelling Challenges in the design of the primary coupling (the coupling between an external unit and the intended internal magnet) include the consideration of actuator sizing to take into account various possible uncertainties in the context of surgical task, consideration of sensor feedback, effect of anchoring magnets, design of compact mechanical transmission to the surgical manipulator on board the internal unit. Furthermore, order of the model needs to be taken into consideration. A rigid body such as the internal unit, has a 6 DOFs in 3D space relative to the external unit. A simplified model can consider the only intended motion, such as the rotation of a rotor, as a DOF in its equation of motion and regards the other DOFs as rigid constraints. This approach will ignore the facts that these other DOFs are not perfectly rigid, for example, the distance between the external and internal unit created by the abdominal wall is not rigid, but perhaps better modelled as being viscoelastic.

As multiple degrees of freedom are required in the operation of the surgical instruments, multiple sets of magnetic couplings
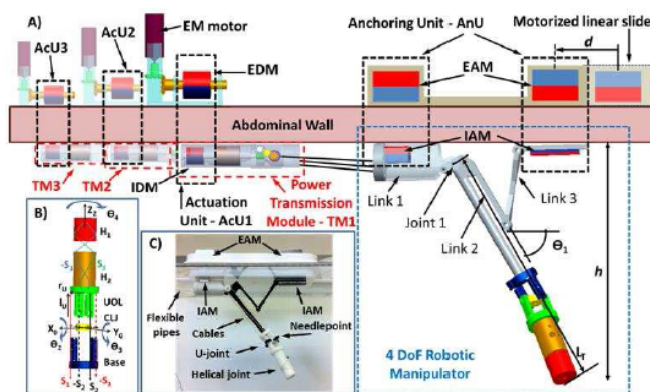
need to be implemented. This creates a challenge in the optimising of the placement of the magnetic couplings. It is desired that the primary coupling between an external unit and its paired internal unit are as strong as possible. At the same time, it is desired that the effect of secondary coupling, which is the coupling between a magnet on board an internal unit with all other magnetic fields present in its vicinity other than that of the primary coupling is minimised. Shielding can assist in this respect but the placement of the multiple sets need to be well designed.

Task Execution and Control In order to execute a desired task such as retracting, cutting or suturing, an appropriate control strategy is required for the resulting surgical manipulator. The main challenge in the control of these instruments is the high level of nonlinearity in the model of the system, which requires design of controllers that take into account the uncertainties in the model, misalignment problem and variable abdominal wall thickness. Another challenge is that the controllers require feedback measurements such as the position and velocity of the permanent magnet rotor on board the internal unit. However, in many applications, due to limitation of the manipulation space and sterilisation requirements, it may not be practical to place any sensor on board the internal unit making the controller implementation even more complex as robust parameter estimators should be developed and incorporated in control of magnetic instrument.

B. Clinical considerations

For abdominal surgeries, particularly in the MIS and LESS approaches, the main considerations of the design of the surgical instruments are the factors which impose constraints onto the current devices, such as the incision size and the workspace within an insufflated abdomen. Furthermore, the layout of the environment would determine the dexterity required to perform the surgical tasks.

1) **Incision size** In order to reduce trauma and loss of insufflated abdominal pressure during surgery, medical practitioners recommended the optimal sizes of abdominal incisions in the MIS environment for available surgical port sizes ranging from 5mm to 12mm [8]. In LESS, only a single umbilical insertion point ranging from 2.5 cm to 3 cm [97], [98] is required while incision will only be made on the stomach, colon, rectum and uterus walls for NOTES.

2) **Insufflation and workspace** Surgical procedures also recommend an internal abdominal pressure during insufflation to be between 12 mmHg to 15 mmHg to avoid disruptions to the blood flow among organs [99], [100], but this is dependent on the size of the patients (i.e. higher pressure might be needed for patients with bigger physique) [101] as well as the surgical position a patient is placed in [102]. Apart from that, the mechanical properties of insufflated abdomen and the volume of workspace within the abdominal cavity have been studied to aid the development of surgical tools. Song *et al* [103] utilised a motion tracking technique to simulate the motion and position of markers placed on

the abdominal wall during insufflation. From the model analysis performed, it was reported that the abdominal wall experienced a maximum displacement of 40 mm at the highest point (i.e. the centre of the abdomen) among the 18 patients in study. It was also observed that the human abdomen, which is initially cylindrical in shape, becomes a domed shape after intra-abdominal insufflation pressure reaches 12mmHg, with an average abdominal cavity volume to be $1.27 \times 10^{-3} m^3$.

3) **Abdominal wall thickness** Statistical studies showed that the average abdominal wall thickness among average build patients is approximately 2cm while among obese patients, the average thickness is around 8cm [104]. External PMs of the appropriate sizes are required to cater for different wall thickness. Best *et al* [105] performed an experiment to evaluate the furthest intermagnetic distance the PM magnetic coupling strength can withhold for their current MAGS platform. The experimental platform was constructed with a robotic arm attached with various sizes of the external PMs (i.e. Neodymium-iron-boron (NeFeB) magnets) coupled to intra-abdominal surgical devices (i.e. with the heaviest device weighing 39g). Force sensor readings were recorded as the robotic arm moves at an incremental distance of 0.5mm over a 10cm range away from the MAGS surgical device using the various sizes of external PMs. The exponential decay of magnetic field coupling force over distance was demonstrated from the force sensor readings. It was reported that the setup (i.e. using a dual stack NeFeB magnets weighing 583g as the external magnet) permitted a maximum intermagnetic distance of 4.78cm with the heaviest load of 39g. For larger intermagnetic distances, bigger and thus heavier external PMs are required. This leads to the considerations on the size constraint during the design of magnetic surgical devices as there could be a limited available space for the external actuation units. Electromagnetic coils have been looked at as the potential solution to providing stronger magnetic fields for a magnetic coupling over larger distances [86].

4) **Triangulation and magnetic field interference** In the experimental study performed by Park *et al* [65], a theoretical distance of 3cm between two sets of external and internal magnets is sufficient to create triangulation without significant magnetic field interference. Nevertheless, in the actual laparoscopic procedures, a distance of 5cm was experimentally demonstrated and thus recommended, in order to reduce the possibility of collision and minimise magnetic interference between different magnet pairs.

5) **Robotic specification for defined tasks** The studies towards the design of magnetic-based surgical instruments have provided some general guidelines and specifications for future improvements. Table I shows some desired tool specifications from the existing developments.

6) **Sterilisation process** Devices with on board electronics require low temperature sterilisation technique that are

normally more expensive and time demanding. Magnets can be manufactured under Curie temperature, i.e. above which there is loss of magnetic properties, which can withstand autoclave sterilisation (132°C). The possibility to include only passive parts on the internal unit can potentially allow cheaper and faster sterilisation techniques for magnetic surgical instruments.

TABLE I: Desired DOF, force and speed at the end effector for difference surgical-assist devices

Surgical-Assist Device	DOF	Force [N]	Speed [deg/s]	References
Tissue Retractor	1	6	N/A	[106]–[108]
Surgical Camera	2	0.2	18	[109], [110]
Surgical Manipulators	6	5	360	[111]–[113]

VI. CONCLUSION

The advances in surgical instruments have played a significant role in the reduction of surgical trauma on patients. The evolution of surgical applications to the current popular approaches of MIS, LESS and NOTES integrated with the use of magnetic actuation emphasizes the benefits of magnetic systems in the field of abdominal surgery. The transmission of actuation forces and torques across the abdominal wall by means of magnetic coupling between the external magnetic actuator and the internal surgical device embedded with magnets, enables the surgical devices to be deployed intra-abdominally without a rigid link connection to the outside. This provides the freedom for the placement of the internal device within all quadrants of the abdominal cavity without compromising manipulation dexterity, triangulation and actuation forces. The realisation of such magnetic approaches has been explored through the use of permanent magnets as well as electromagnetic coils for more control variables. The resulting surgical instruments, residing completely within the abdominal cavity during the operation, need to be designed to cater for the requisite of the surgical task and environment. With future advancement in sensing and localisation of multiple DOFs magnetic interaction (e.g. in LMA and LEMA), effective and dexterous magnetic surgical platform will greatly contribute to the abdominal surgical procedures. The concept of magnetic-based techniques in robotic surgery therefore demonstrates great potentials for surgical innovations that could replace conventional abdominal surgery, elevating the surgical robotics field to the next technological level.

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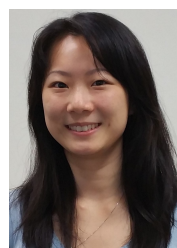
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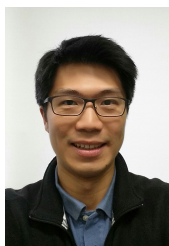
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