A Preface in Electromagnetic Robotic Actuation and Sensing in Medicine

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Abstract With the advancement in robotics technology, medical field is evolving more with minimally invasive to noninvasive procedures. Minimally invasive surgical procedures have gained ever-increasing popularity over the past decades due to many of their advantages compared to traditional open operations, such as smaller incisions, faster recoveries, fewer complications, and shorter hospital stays. Robot-assisted minimally invasive surgery promises to improve the precision, dexterity, and stability of delicate procedures. Among these technologies, there is a demanding clinical need to progress the field of medical robotics in connection with noninvasive surgery. For this, the actuation and sensing in the future robotic surgery systems would be desired to be more wireless/untethered. Out of many promising wireless actuation and sensing technologies, one of the most patient friendly techniques to use is electromagnetic or magnetic actuation and sensing for feedback control and manipulation. In this book, we have intended to elucidate the recent related research and developments behind the electromagnetic actuation and sensing implemented in medical robotics and therein.

1 Electromagnetic Actuation

In a magnetically controlled actuation, the core components can typically be the actuator (moving portion) and the stators which are typically the external magnetic field generators. This is analogous to active magnetic bearings (Chap. 5) where the actuators are the rotors, and the magnetic fields are generated from the stators. Common field generation setup includes Helmholtz and Maxwell variations (Chap. 2) or arbitrary multipole electromagnetic coils (Chap. 5). The actuated region can be in the form of distal tips for catheters (Chap. 4) or small microparticles/microrobots (Chap. 2).

As discussed in Chap. 2, Helmholtz coil is a specific configuration to generate an uniform field at a region of interest (ROI) where EM field is usually referred

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to as the alignment field. Maxwell coil generates a gradient field where the scalar contribution at the ROI is near zero. In general, the alignment fields exhibit a torque on the permanent magnet or soft magnetic target such that it rotates to align and associates with the magnetic fields generated about the moment of inertia [7].

Maxwell gradient coils provide the displacement force to move the particle. The number and type of coils can be designed according to the requirements in degrees of freedom (DOFs) needed. The total contribution is popularly arranged in a matrix [7]. The electromagnetic fields generated are in turn controlled by the current flowing through the coils. More complex variations of Helmholtz Maxwell designs include the Halbach cylinder [18], saddle coils [15], and square coils [12]. The increasing complexity of the coil design aims to either increase field uniformity or field strength. In general, the most primitive Helmholtz Maxwell combination is an easier to manufacture setup but requires a more robust controller for precision. It is also noteworthy that current designs which require closing the control loop present a limitation in terms of the sensor. More prominent techniques utilize sensors, which are eddy current sensors and hall effect sensors, to feedback position information to the controller; hence these methods are preferable over image processing alternative which requires an external camera [35].

Other than Helmholtz and Maxwell designs, alternative multiple electromagnet pole designs have been proposed (US7173507, US20120143127A1). Octamag [19] uses eight electromagnets to control the 5DOF microrobot for use in ocular surgery. A microelectronic [10] fabricated design was also able to do particle filtering and separation by generating unique field from the complex electronic circuit design. These methods generate less uniform field which could be an issue for control [2]. In a more recently published paper [22], a combination of electromagnetic coils and permanent magnets was demonstrated for camera positioning in laparoscopic surgery.

2 Magnetic Actuated Robots

In Chap. 2, it is worth looking into the field of magnetically actuated microrobots/particles, and it is also highly similar to magnetic catheter actuation (Chap. 4), which can also be seen as a particle control if only the distal tip contributes to magnetic actuation. Developments in magnetically actuated microrobots have potential to contribute improvements toward present methodologies in magnetic catheter actuation. The magnetic manipulation of the small particle does have some differences, for example, having a fabricated tail to assist motion [1, 24]. The tail is usually of a helical form which does not have apparent use in guide wires, but it has been shown that it could have potential value in mediating calcified arteries [17]. Common materials that have been considered are NdFeB permanent magnet, Ni, and iron oxide for microparticle fabrication. Further, for small robots, piezoelectrics have been implemented for locomotion [5, 20]. Other than magnetic propulsion, acoustics such as from piezoelectric can serve an additional function to deliver drugs [34]. The oscillatory magnetic field which is required for piezoelectric stimulation could also be used for steering control depending on the phase lag [21]. For specific fabrication, SU-8 with dispersed magnetic particles was shown to be viable [14]. Octomag's microparticle manipulation is demonstrated to be robust even without Helmholtz and Maxwell coils [23].

3 Magnetic Guide Wire/Catheter

Chapter 4 specifically investigates certain roles of magnetic actuation in clinical procedures particularly for controlling the guide wire or catheter in very complicated cardiovascular environments. The manipulators or catheters bend due to specific magnetic domains along the axis of the guide wire under an imposed magnetic field which could be of a specific configuration. Historically, the bending resulted from the magnet tip can be controlled by introducing a compliant hinge to reduce the force required to bend the guide wire [30]. These manipulators usually have magnetic responsive elements which could be in the form of particle suspensions (Chap. 2), or flexible magnetic material (Chaps. 4 and 6). It was noted that the increase in the number of segments increased the difficulty to control the catheter but enabled a more stable and linear distal portion [31]. There are many geometrical designs of such distal remotely controlled elements, for example, balls, rings, or helical elements to induce bending. Such elements could also be used for guide wire alignment or inducing restrictions to assist bending and positioning of the guide wire. Other than bending manipulation, these elements are also shown to be able to perform lateral advancement, transmission of force, and assist visual feedback.

Additionally, the magnetic navigation system was also simulated to be able to improve the operative procedure and save the fluoroscopy time [28]. By using a glass model of liver and choosing to navigate a highly tortuous path, the magnetic guidance system outperforms the traditional manual methods, both in time taken and the number of bends it is able to achieve. A specific application to ventricular ablation was reported [4, 6, 29], demonstrating the manipulability of a magnetic navigation system in a biophysical environment. Magnetic navigation was argued to be an improvement over traditional manual control for the ablation procedure [27]. The catheter was implanted with a permanent magnet which aligns with the external field generated by the StereotaxisTM system with a field strength of 0.15 tesla at the homogeneous region [9]. Another novel advantage of magnetic navigation is the ability of the catheter to be attracted into the vessel rather than being pushed in, which allows the catheter to be very soft and compliant increasing the safety of the procedure [8]. Other catheters have also been developed to clear plaque and use a combination of Helmholtz, Maxwell, and Maxwell gradient and saddle coils [16] unlike the previous StereotaxisTM [33] which uses two electromagnets. The StereotaxisTM [31] is known to work as an open-loop system, and they have also proposed a closed-loop methodology utilizing the equilibrium equations from the potential energy in the work space. The specific model used can also be referred from this publication [32]. There are also some associated risks of magnetic navigation that are noteworthy. Using MRI, it was studied that heat generated from the magnetic resonance could cause heating of the catheter [26], indicating that traditional guide wires will not be suitable for these applications [25].

4 Electromagnetic Sensing

Magnetic biosensing and detection pose a fertile field of research in the realm of biomedical engineering applications. A potential way to receive a feedback signal from the human body is to use an electromagnetic sensor that is capable of sensing the downstream physiology and processes. For example, biological cells triggered by magnetic micro/nanobeads accelerate traction force for mechanotransduction, which can be sensed by external magnetic sensors. In addition to the microscale, macroscale diagnostic and point of care (POC) applications need sensing mechanism for better health care, faster diagnostics, and therapeutics. Tactile sensing and rehabilitation robotics are some of the exciting paradigms where electromagnetic sensing elements can play a pivotal role and beyond. To make the mechanoreceptors work aptly, the electromagnetic sensor can portray an exciting new regime for flexible electronics and skin prosthetics. Magnetorheological elastomer (MRE) has promising applications in soft, flexible robotics for better human–machine interaction and cooperative control. MRE also has similar mechanical property to that of natural muscle for which can be further served as rehabilitation and tactile sensing in biomedical engineering. On the same hand, minimally invasive surgical robotics and force control in mechanical counterpart need sensor actuation for better motion navigation and planning algorithm as described hereunder.

Overall, the automatic and reliable navigation and motion control or compensation of surgical robots are depending on the motion tracking of surgical instruments and also the surrounding anatomic structures. Many technology advancements have been achieved to address this problem, and we are focusing on magnetic sensing technologies, because of its advantages in terms of size, remotely sensing, flexible passive or active configurations, and also, free of line-of-sight requirement.

To achieve online motion control and planning, it is necessary to gain the real-time position and shape information of the flexible surgical robot. To acquire this information, the flexible surgical robots can be mounted with electromagnetic sensors. The shape estimation algorithm has been developed based on either quadratic or cubic Bézier curves as presented in [3, 11, 13]. Besides electromagnetic sensors, microcameras can also be utilized to assist the navigation procedure. Then with the position and shape information acquired for the flexible surgical robot, the online motion planning can be achieved by modifying the offline planned trajectory based on the feedbacks provided by the sensors in the future.

5 Brief Outline of the Chapters

The flow of the chapters in this book will mostly adhere a bottom-up approach and will be starting from submillimeter microrobotic device driven by external magnetic field to submillimeter magnetic sensing devices. For example, in the initial part of the book, we constrict in the microscale untethered robots and application in the medical community with the help of electromagnetic actuations.

Chapter 2 investigates the field of microbots, which is exponentially advancing its impact on the medical healthcare industry with its ever-increasing potential. It may happen in near future when the sci-fi movie fantastic voyage will be a reality with the help of electromagnetic actuation and precise control. To make this microbot a reality, there still is a huge amount of research needed in order to overcome many different challenges such as (1) smart manipulation with changing *in vivo* pH environment, (2) to sense a cancer cell from healthy counterpart, (3) smooth access to near and farthest abnormal tissues from point of injection, and (4) most importantly to overcome toxicity and biocompatibility issues. In parallel to investigating the microcapsules, we have initiated tracking of microparticle using contrast agent microbubble in the vicinity of medical ultrasound. Magnetic microbubbles which can be controlled by an external magnetic field have been explored as a method for precise and efficient drug delivery. In our lab, a technique for the fabrication of microbubbles encapsulated in magnetic spheres is presented. The resultant magnetic spheres were subsequently imaged using ultrasound, and the encapsulated microbubbles proved to appear as bright spots and resulted in enhanced ultrasound image contrast, as compared to the solid magnetic spheres which appeared dull. A tracking algorithm was then developed for the tracking of the magnetic microbubbles based on optical flow tracking. Further development of the magnetic microbubbles and tracking algorithm can lead to future use of the tracking algorithm in the case of *in vivo* injection of the magnetic microbubbles.

Chapter 3 represents a state-of-the-art approach for magnetically induced soft flexible robots for diverse biomedical applications. Soft, flexible yet resilient, adaptable polymers can be introduced with magnetic micro/nanoparticles for changing mechanical dimensions upon magnetic actuation. Soft force sensors are very much needed for the biomedical rehabilitation patients in general for light and efficient tracking with the outside environments. In this aspect, MRE has potential applications for force sensing and tracking which has been focused in this chapter in general. To support our design and hypothesis, we have given some initial experimental results for proof of concept and future scope to dig more into this realm. Soft magnetic polymer has an inherent property of high remanence like permanent magnets which can be refined to meet ever-increasing demands in safe regulated medical environments. The grating-based sensors like the Low Period Fiber Grating (LPFG) and Fiber Bragg Grating (FBG) are commonly used to measure the intensity or wavelength variation. These require a complex signal processing technique and difficult to minimize the effect of temperature and nonlinearities with simple fabrication. To solve the above problems and for wider applications, e.g., in rehabilitation and assistive biomedical device, bend sensors need to be more flexible, stable, cost-effective, and human friendly. Taking advantage of this soft magnetic polymer, in Chap. 3, we propose a novel soft-squishy and flexible bend sensor by determining the relationship between inductive changes and bending angle. This bend sensor employs flexible wire embedded in a silicone elastomer with different permeable core. The principle notion is to have a comprehensive analysis of the change in the morphology of the sensor with bending angle which can be translated to the inductance generated therein.

Chapter 4 concentrates on progressing the existing medically proven concept of catheter and guide wire robotic system under magnetic actuation. Surgical robotics is a growing field with substantial benefits to professionals and patients but one limit of conventional key-hole surgical robotic systems is the requirement for mechanical information to be conducted along the path of the robot. This can result in complications such as buckling and entanglement due to the tortuous environments. In this realm of catheter and guide wire system, the electromagnetic actuation holds a promising chapter. This chapter will discuss the method of using a tether-less electromagnetic coupling to transmit the mechanical information. Our lab has devised a small-scale prototype demonstrating electromagnetic deflection principle. In addition, when compared to the larger devices, this prototype is more portable and easier to integrate with existing equipment without the need for bulky equipment. This chapter presents an overview of electromagnetic actuated system which will further cover the design principles of magnetic actuated catheter robot taking example from in-house prototypes, such that the reader will be capable of designing and fabricating a similar art. A key parameter of electromagnetic catheter systems is the bending angle and will be addressed. The key considerations for an electromagnetic actuation and brief clinical perspectives are introduced for the design considerations of an electromagnetic catheterization system.

Chapter 5 has introduced a novel microrobot system based on magnetic levitation techniques for better handheld precise motion control in surgical applications. This chapter in part is to counterbalance the persisting challenges in (1) economy, (2) complexity, and (3) space requirement of a bulky traditional master–slave remote operation. In this chapter, at first, the primary components and working principle of magnetic suspension bearing system are introduced. Then, the configuration analysis of magnetic actuator is presented, and the design method of magnetic bearing with current bias is introduced in detail. The design of 1DOF, 3DOF, and 4DOF magnetic actuator system is described in detail. Finally, the expectation of magnetic actuator system is presented for the small volume and self-sensing destination (Fig. 1).

Chapter 6 will give a comprehensive overview of magnetic sensing applied to surgical environments, discover recent developments, and show a possible future of the magnetic tracking research. The chapter will first give an overview of how the magnetic sensing technology works. After that, the sensing applications will be given in detail in the context of three typical medical applications: (1) magnetic sensing for wireless capsule robots; (2) magnetic sensing for in clinical particles; and (3) magnetic sensing for flexible surgical robots.

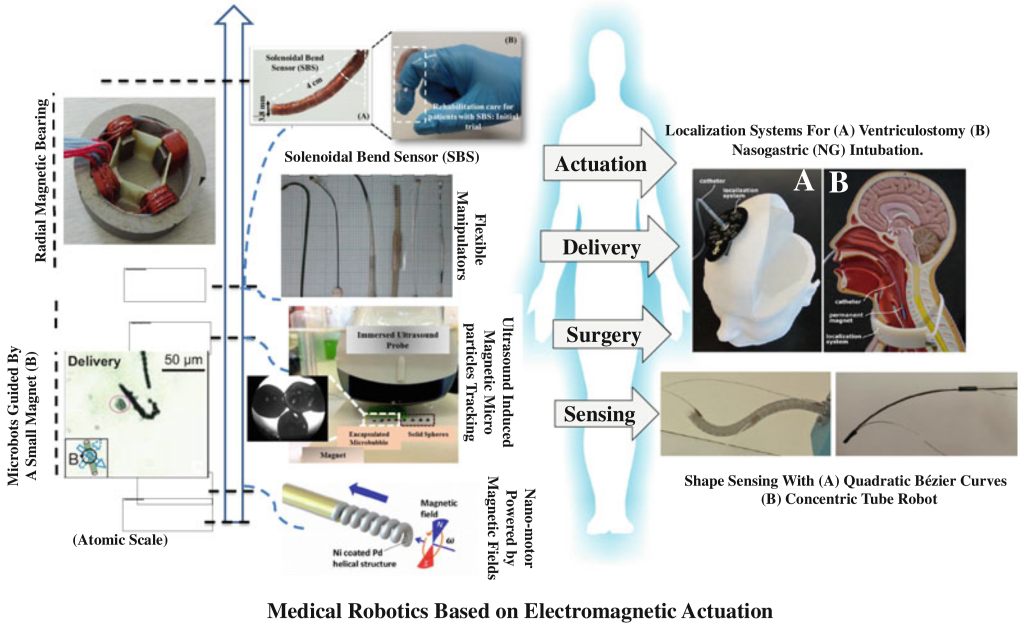

Fig. 1 A scaled-up view with dimension to show the distribution and arrangement of book chapters. This illustrates organization of the book chapters in the context of electromagnetic actuation and sensing in biorobotics. *Bottom left*: microbots in Chap. 2; *Upper most*: (a) Soft Solenoidal Bend Sensor (SBS) with flexible coil embedded in polymer and Sensor used to detect the bending angles of finger Distal Interphalangeal joints (DIP) joint as illustrated in Chap. 3. *Upper Middle*: Magnetic actuated catheterization in Chap. 4; *Upper left*: Magnetic bearing for micromanipulations in Chap. 5; *Right*: Magnetic sensing in Chaps. 6 and 7; and finally ultrasound based magnetic microparticle tracking using contrast agent described in Chap. 8.

Chapter 7 will introduce more advanced topics involving magnetic tracking, signal estimation, artificial intelligence techniques in motion tracking, and navigation systems, which are paramount for both safety and efficacy in a variety of medical interventions and procedures. Magnetic field-based tracking technology becomes appealing for many applications. It utilizes the phenomenon that the distance and orientation of the magnetic source will change the amplitude and direction of the local magnetic field in space. By mapping the measurements of the local magnetic field to the distribution of the magnetic source, it can estimate up to six degrees of freedom (DOFs) positional information (both position and orientation). Because the magnetic fields are of a low field strength and can safely pass through human tissue with least interference, it can be used for tracking instruments/tools inside the human body without line-of-sight restrictions. In this final book chapter, the magnetic field model often used in passive magnetic tracking is first reviewed. Along with this, an overview of the working principle and methods of the passive magnetic tracking technology is presented. Then, two different localization methods are described, namely, the inverse optimization method and the direct ANN (artificial neural network) method; the advantages and disadvantages of the two methods are discussed using two actual medical intervention procedures for practical illustration. Lastly, some limitations and challenges faced by the passive magnetic tracking are discussed. Conclusively, through this chapter, implementation of the technology in actual medical interventions was also be demonstrated, and the challenges in the development of this technology are explored and discussed therein.

Ultrasound transducer has been used extensively since last few decades for monitoring living organism in medical diagnostics as well as in therapeutic applications. The non-thermal effects of ultrasound like cavitation and microstreaming are well regarded for therapeutic applications than only for medical imaging and tumor ablation processes. Here, in Chap. 8, we unveil motion of magnetic particles captured using ultrasound imaging with contrast-enhanced microbubbles. Ultrasound videos were captured and analyzed by image tracking algorithm to determine the efficiency and accuracy of the algorithm. It is necessary to ensure an efficient and accurate tracking method of the particles in order to evaluate future *in vitro* or *in vivo* applications of the microbubbles, when implanted into an enclosed system and imaged using ultrasound. Microbubble-generated therapy in deep tissue with ultrasound-induced non-invasive administration is envisioned to be ongoing popular choice as long as we can safely administer drugs using accurate magnetic navigation, control. Encapsulated microbubbles enhance the ultrasound imaging contrast, allowing the fabricated magnetic particles to be effectively tracked using the created algorithm. For future development, *in vivo* like conditions can be used, such as the presence of other particles, for example, red blood cells. The fabricated magnetic microbubbles could be further used as test particles for external manipulation systems for drug delivery.

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