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Review Article

Biomedical and Micro-Robots: An Overview of Recent Developments

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Abstract: This paper aims to provide an overview of recent challenges in the development of micro-robots for future biomedical applications. This paper first considers a comprehensive survey of the state-of-the-art in medical micro-robots. Consequently, it investigates the critical aspects and emerging ideas associated with designing of such medical micro-robots in order to navigate in viscous environments and inspire future research for healthcare applications. Potential biomedical micro-robots are used for a wide variety of applications into different organs of the patient's body, such as clearing heart occlusion, treatment of Nephrolithotomy, minimally invasive surgery, micromanipulative, released into the bloodstream and targeted drug delivery. Challenges and emerging concepts include functionality, powering, robot localization, communication and safety have been proposed, thereby leading to enable an extensive range of medical operations locomotion features, obtain and process information, being able to operate within specific constraints. This review provides details insight of medical micro-robot developments and the existing solutions for challenges and emerging concepts paving the way for designing such a medical micro-robot for operation inside, fast recovery and increased quality of life of patients.

Keywords: Biomedical Robot, Micro-Robots, Minimally Invasive Surgery, Treatment of Nephrolithotomy

1. Introduction

The advent of robotic devices at the millimeter and micron scale, may in the near future bring a revolution in medicine [1–3]. Due to the potential impacts (scientific and societal) of micro-robot would be application of their in healthcare and medical fields. There are currently existing tethered medical devices such as flexible endoscopes and catheters, two major challenges raised: (1) theoretical and (2) experimental. Thus, recent advances micro-robots as an alternative to the application of medical could a broad spectrum of complex and small regions of the human body covering, including gastrointestinal tract, brain and spinal cord, blood capillaries (vascular) networks, inside the eye and kidneys while being minimally invasive and could even enable access to unprecedented submillimeter size regions inside the human body, which have not been possible to access currently with any medical device technology [4], [5]. The size of the miniature biomedical robot ranges from few micrometers to several centimeters. In micro-robots, mechanics dominated by microscale Volumetric (bulk) forces such as buoyancy propulsion and inertial are insignificant or comparable to surface area forces (surface tension, friction, viscous forces, adhesion, and drag). In micro-robot, macro scale forces such as bulk forces dominate their mechanics. Features of the proposed two approaches requirements to designing miniature medical robots:

(1) On-board: micro-robot contains On-board components

to operate autonomously or remotely controlled and be much smaller than the robot size [6]. (2) Off-board: micro-robot contains Off-board components to operate autonomously or remotely is externally actuated and may be larger than On-board components [6]. In 2000, R. S. Fearing et al have first presented robots which called micromechanical flying insect [7]. S. Hollar et al in 2004 was introduced a solar powered 10 mg silicon robot [8]. A. M. Hoover et al in 2008 reported an autonomous crawling Hexapod robot and Centimeter-scale with advanced abilities for actuation and control [9]. K. Y. Ma et al in 2013 demonstrated an insect-scale robot that controlled flight (with off-board power) of a biologically inspired [10].

Moreover, researchers were inspired by nature and biology, design and supply capabilities and diverse applications with a high potential for medical applications such as bacteria-inspired swimming propulsion [11], laser-powered micro-walkers [12], catalytic self-propelled microtubular swimmers [13], bacteria-propelled beads [14], [15], magnetic resonance imaging (MRI) device-driven magnetic beads [16], magnetically driven millimeter-scale nickel robots [17], steerable electrostatic crawling micro-robots [18], and bio-inspired micro-robot with multi-functionality structure [19].

In this review, challenging design topics envisioned future medical micro-robot would be able in-vivo applications and carry out complex medical operations. Micro-robots inside of patient's body must carry the necessary tools and ultrafine on-board in the target area and "non-invasive" way. Existing challenges for micro-robots potential in biomedical applications briefly is described, including powering, robot localization, communication, motion control, functionality for multiple tasks with exact and advanced technologies in the near future.

2. Biomedical Applications of Micro-Robots

One application of small untethered robots that captured the attention of early researchers was in the gastro-intestinal (GI) tract. This passageway through the body, which can accommodate relatively large objects, is where the first commercial systems have been applied. These untethered, endoscopic capsules are the size of a pill and are simply swallowed by the patient. They capture video images from the GI path with their imaging and illumination systems while naturally traveling through the path. Other researchers proposed robotic systems with locomotion and biopsy capabilities. Typically, robots built for the GI path are miniaturized mechatronic systems with many components of conventional design. It is in the more challenging parts of the human body where truly microscopic sized robots would be needed that MEMS technology provides the only solution. Robots swimming in the blood stream or inside the vitreous humor (a clear, gel-like substance that fills the posterior cavity of the eye) have been envisioned. A reoccurring theme with such micro-robots is the use of ex-vivo generated magnetic fields to transfer energy to the robot. Whereas MEMS and VLSI technologies have accomplished the miniaturization of structural and electronic components, a corresponding breakthrough in energy storage was not been achieved. This issue comes to center-stage with sub-mm sized micro-robots for cardiovascular or ophthalmic applications.

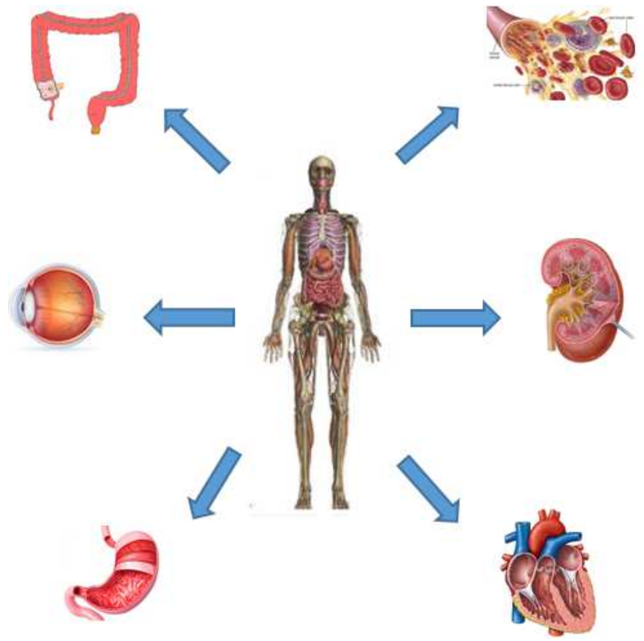

Figure 1. Applications of micro-robots in different organs of the patient's body.

3. Challenges and Emerging Concepts in Biomedical Micro-Robots

To enable high-impact biomedical applications of miniaturized mobile robots, many fundamental challenges need to be addressed. As the functional robot size goes down to the millimeter scale and below, design, fabrication, and control of these systems require design principles which greatly differ from that of macro scale robotics. Moreover, medical activities inside the human body will require additional tasks such as feedback from the environment and communication with the operator. In this section, we discuss the challenges associated with miniaturization of untethered biomedical robots from their initial design to the preclinical testing steps. We also provide a future outlook toward a solution in light of the recent advances addressing some of these challenges.

3.1. Components

The ideal micro-robot for medical applications is fully autonomous and it is able to position itself, perform diagnosis with various sensors, locate itself accurately (position accuracy of 1 mm), transfer data and receive commands by wireless communication and perform medical intervention within the human body. Such a system is a goal of the research, even though several medical micro-devices already been possess some robotics aspects as shown in the previous section. The subsystems that are necessary for an autonomous swimming micro-robot are also under development. In this section, we would like to present the essential components necessary to build an autonomous swimming micro-robot. Dario [20] introduced and Ebefors and Stemme [21] developed an essential component list for a micro robot. The authors suggested the following sub-system division: Control Unit (CU), Actuation for Positioning (AP), Power Source (PS), and Actuation for Manipulation (AM). In the case of medical micro-robots one should add also the following parts: Sensor Unit (SU) and arguably Communication Transceiver (CT); one can include it in the control unit although the communication is usually developed separately from the control.

The different sub-systems are in different development stages part of them are commercially available, such as CT and CU, part is in advance development stages such as SU and AM and part are still in early development stages. The major challenges in medical micro-robots are AP and PS which are the enabling technologies for the full micro system. The efforts and achievements in the different subsystems described above will be summarized below.

3.2. Telemetry and Challenges

Data rates are limited in current unidirectional telemetry links for video signals, which limit current image transmission frequency from 2 to 4 Hz. Paths forward towards more rapid imaging include improved image compression algorithms and/or enhanced telemetry link technology, with electric field propagation being the most promising current technology. In designing a telemetry link, one must be concerned with not only keeping electrical power consumption low and data rates high, but also maintaining transmission signal power within medically safe limits [22] without sacrificing transmission link reliability. Robotic devices often require bidirectional communication, and Zig-Bee is the most promising current technology that has been used in this application.

3.3. Functionality

In the millimeter scale, although active imaging is possible with current capsule micro-robot, this function is primarily used for post-procedure diagnosis. In the future, it is imperative to go beyond this to advanced image processing for diagnosis of visually undetectable disease [25], to map the 3D environment of the given organ using visual simultaneous localization and mapping (SLAM) [26] or optical flow based advanced motion detection algorithms to predict the capsule motion precisely [27], and to propose new active focusing and 3D illumination methods to improve the imaging quality and diagnosis precision [28].

On the micron scale, the only practically available site for micro-robot functionalization is its surface. Porous soft materials can also allow cargo encapsulation inside their 3D body.

This would be a very useful strategy as it allows the higher amount of cargo loading compared to the 2D surface. There has been extensive experience over drug encapsulation and release for targeted therapy and controlled-release applications, which might be directly transferred to micro-robotic applications [29]–[31]. For this purpose, a whole micro-robot can be fabricated as a big cargo depot, which will significantly prolong the impact of single dose administration.

In accordance with the special medical requirement, micro-robot surface can be modified with operational micro-tools enabling the sensing of disease diagnosis, therapeutic functions, e.g., targeted drug or gene delivery, and surgical functions, e.g., cauterization and clearing clogged blood vessels.

In this sense, mechanical micro-grippers could be promising micro-tools for ablation and biopsy as well as drug/ gene delivery [23], [24]. Similar micro-tools for drilling and heating local tissue sites could profoundly improve noninvasive surgical operations, particularly for removing tumor in deep tissue sites. High throughput or organized operations could find pervasive use in biomedicine. A typical example of micro-robot swarms piece-by-piece building tissue scaffolds could revolutionize tissue engineering.

3.4. Localization and Challenges

Since the GI tract is a long tubular structure that folds upon itself many times and is free to move within the abdominal cavity, it is a challenging environment in which to localize capsule position. Furthermore, the GI tract lacks straightforward landmarks, making discernment of capsule location from image information difficult even for trained physicians. However, identifying the physical location of capture of each capsule image is important in both diagnostic and therapeutic applications of WCEs. This has lead to a number of innovative approaches to the localization problem, as reviewed above. However, these systems are currently at the proof of concept stage, and it remains unclear which will be the most useful and easily implementable, while providing sufficiently accurate information, in future clinical WCE applications.

3.5. Communication

While many commercial transceivers are available for capsule micro-robot, no one has tackled yet the challenge of wireless communication with micro-robots inside the human body or communication among a large number of micro-robots, which could be crucial for data or information transfer from the robots to the doctor and vice versa and micro-robot control and coordination. Magnetic actuation was proposed as a promising wireless strategy for cooperative [32], [33], [34] and distributed [23], [34] micro-robotic tasks. However, the effectiveness of distributed operations via magnetic actuation drastically diminishes with increase in the number of micro-robots in the team. Further, magnetic actuation is an open-loop controller, lacking autonomous decision-making based on real-time sensing of changes in the environment and state of individual micro-robots. In this regard, principles that govern the social behaviors of biological microorganisms could be a valuable source of inspiration to address control and coordination of micro-robot swarms.

Microscopic species exhibit collective behaviors in response to environmental stimuli, which are sensed and transmitted among individual species by physical interactions and/or chemical secretions [35], [36]. Dictyostelium discoideum is a well-known example of such microorganisms, which, upon self-organization into a hierarchical colony with up to 105 residents, can reconfigure itself and migrate as a single unit [37]. Quorum sensing is another cell-to-cell communication process used in bacteria for sharing information among the population and eliciting a collective reaction [38]. An intriguing property of quorum sensing is that the population density is monitored in real-time by the whole colony and a communal response is elicited as a result [38]. This strategy is particularly inspirational for developing a population density-driven switch for micro-robot operation inside a body. Micro-robots gathering inside a specific body site and operating only after their population reaches a particular size would be a highly effective strategy.

3.6. Vision

The only location where the circulatory system is observable from the outside of the body is the retina of the eye. This makes imaging and localizing intraocular micro-robots possible through simple components such as microscopes and cameras combined with image-processing techniques. However, the complicated optics of the human eye make accurate localization difficult. One proposed method for tracking an intraocular micro-robot uses a purposely defocused view acquired from a single microscope [39]. However, this method does not properly account for the optics of the eye. A custom single-aspheric-lens ophthalmoscope has proven better for the generation of wide-field-of-view focused images and for localization [40]. Detecting and segmenting ametallic micro-robot from the retinal background can be accomplished using color-space techniques [41].

3.7. Powering Micro-Robots

For a technical discussion on the design of wireless micro-robots, we must begin with power. With micro-robots, even more so than with traditional robots, we must be acutely aware of the methods available to store, harvest, and transmit power, and we must acknowledge the strict limitations that power consideration will put on any practical design. Without addressing power from the beginning, it is difficult to transition from prototypes to fully miniaturized wireless devices.

3.8. Control Unit

Control units of micro-robots are usually limited to driving circuits for the actuators [43]. The endoscopic capsules that are developed around the world are using IC (Integrated Circuit) design to process the input from the SU (usually only a micro camera) and prepare it for the CT [42, 43]. Casanova et al. [44, 45] an MXS chip for the control of the AP, AM and CT.

The CU have to be specially designed for a medical micro robot because of the specific requirements and the necessity of low energy consumption [42]. A good example of the extreme limitations of micro robots is the I-Swarm project [46], in which a control unit was made for a 3 * 3 * 3 mm^3 robot with the power consumption bellow 1 mW.

4. Conclusions

This dissertation provided an overview of recent challenges in the development of micro-robots for future biomedical applications such as colonoscopy according to Minimally Invasive Surgery, medicine/gastroenterology. The analysis of Challenges and emerging concepts of robotics (e.g. functionality, powering, robot localization, communication, motion control and safety) with the exciting techniques and new tools enabled by MEMS technology in order to significantly improve the quality of our lives. In conclusion, we believe that the combines the established medical and robotics in collaboration with leading experts cause important role for the success of this technology of the future.

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