博士論文（要約）

Navigation of an Intravascular Medical Microrobot Using a Magnetic Field
(外部磁場を用いた医療用血管内マイクロロボットのナビゲーション)

プロエトナー　ペーター

The cardiovascular system is an often selected environment to be studied for treatments. It allows minimal invasive access to numerous locations in the human body and therefore is interesting for medical microrobotics. Targeted drug delivery is frequently mentioned as motivation for microrobots in the cardiovascular system. The worldwide leading cause of death are cardiovascular diseases, which gives another intriguing research field for advanced treatments with microrobots.

The complexity of the cerebrovascular system results in challenging treatments of hemorrhagic strokes by endovascular coiling. Endovascular coiling is the preferred method because of its minimal invasive nature. However, the control over the catheter tip in the cerebrovascular system from the proximal end at the thigh is a limiting factor. Certain regions in the cerebrovascular system cannot be reached this way and make a craniotomy necessary to allow for clipping the (ruptured) aneurysm from the outside. This invasive treatment generally requires an increased recovery time and is associated with an increase in morbidity. A minimal invasive treatment with increased maneuverability to allow endovascular treatment of all aneurysms would be desirable. Magnetic tip catheters navigated by an electromagnetic field have been proposed and used in combination with automated advance and retraction mechanisms. Currently, the magnetic tip catheter system is improved to be tracked by a single computed tomography (CT) C-arm. The next step in increasing the maneuverability inside blood vessels would be an electromagnetically propelled microrobot. By attaching a microrobot through a tether to the guidewire tip, the maneuverability of the guidewire could be increased without the necessity to modify the guidewire in any other way. The increased number of minimal invasive treatments would result in reduced trauma for the patients and probably a reduced morbidity rate.

Several research groups investigated transport possibilities of microrobots for medical substances because of their interest in drug delivery or sensory capabilities. The less intense researched area is the navigation of microrobots in the geometrically complex cerebrovascular system in combination with the pulsatile blood flow and generally strong blood flow velocities. First priority has to be the eventually safe and highly robust controllability of the microrobot.

Electromagnetic fields are often chosen for propelling endovascular microrobots. Electromagnetic fields allow for a precise control of the microrobot from a distance with health hazards similar to Magnetic Resonance Imaging (MRI). Health hazards include magnetic materials inside the body, exceptionally high electromagnetic field gradients, and rapid electromagnetic field strength changes. Generally, rotating or gradient fields are used. MRI scanners can be used for alternating gradient field propulsion and tracking of a microrobot. However, the switch between both functions limits the control and tracking speed. Further, it requires to customize the standard MRI control system. Various propulsion strategies have been investigated for one- and two-dimensional microrobot navigation. Three-dimensional navigation demonstrations were mostly limited to small workspaces.

This thesis focuses on the investigation of the state-of-the-art propulsion concepts and the therefrom derived new propulsion method with two mobile and nonlinear electromagnetic coils to navigate a microrobot in 3D. First simulations are confirmed with preliminary experiments on an existing experimental setup. This is followed by the design of an experimental stand to proof the concept of propelling a microrobot in 2D with only two electromagnetic coils instead of four or eight coils (two Helmholtz and two Maxwell coils per dimension) as in a widely used setup type. After the 2D experimental stand, a second, 3D navigation experimental stand was design and tested. The electromagnetic coils were attached to a pair of industrial robotic arms. Each robotic arm had six degrees of freedom and had one electromagnetic coil mounted. The robotic arms could be controlled independently. The described propulsion strategy allowed free positioning (three translational degrees of freedom) and orientation (two rotational degrees of freedom) of the microrobot. One rotational degree of freedom was not taken into account as the electromagnetic coils and the microrobot were axisymmetric. Compared to static systems, the industrial robotic arms increased the workspace and made the system more flexible. The main benefits of the here described system can be summarized as:

- Reduced number of electromagnetic coils (compared to a stationary system with six Helmholtz and six Maxwell coils)

- Reduced complexity of the overall system (compared to a stationary system with six Helmholtz and six Maxwell coils)
- Flexible workspace size, easy positioning of the workspace, and numerous applications throughout the body
- Sufficient electromagnetic force generation to counteract blood flow

The 2D experimental stand first developed had a limited workspace compared to the clinical requirements and therefore focus was put on increasing the workspace further for the 3D experimental stand.

Regarding the microrobot, research was focused on control strategies rather than the microrobot's design. The required microrobots size compared to blood flow velocity that could be counteracted was analyzed early on and confirmed in their outcome with preliminary experiments. The 2D experimental stand confirmed that the control of the microrobot with two nonlinear electromagnetic coils was feasible. With the lessons learned from the 2D experimental stand a 3D experimental stand was developed. Especially important for the 3D control was a strategy to control the microrobot parallel to the coil surface and not only towards the coil surface. The parallel movement of the microrobot allows for navigation of the microrobot along blood vessels were the human body or other equipment blocks the optimal position of the electromagnetic coil(s) in the desired movement direction. Additionally to coils and industrial robotic arms, controllers, cameras, a pump, blood vessel phantoms, and a PC were necessary. 2D experiments with the 3D experimental system are compared to the 2D experimental setup. 3D experiments are checked for their clinical applicability. Results are discussed regarding their shortcomings towards the previously defined requirements. Future development opportunities are described. This includes a new electromagnetic coil, which would increase the electromagnetic field strength significantly. Simulation results are shown, which would allow realistic blood flow counteraction in the whole cerebrovascular system.