University of Southern California

EE590: Directed Research

Control of Bio Nano Robots

Author:
Vinaykumar S. Hegde
Graduate Student
Department of Electrical Engineering.
University of Southern California, CA
(USC ID: 4809250026)

Advisor:
Prof. Edmond A. Jonckheere, Ph.D
Professor of Electrical Engineering and Mathematics
University of Southern California, CA.

1 Introduction

Advancements in fields of robotics and nano materials have given rise to whole new spectrum of developments in nano-robotics. Sub micron size and precision manoeuvrability brings a perfect application of nano robots in the field of medicine. Increasing advancements in the field of fabrication of nano materials has excited the scientists and innovators to think of treating patients at cellular levels. This report summarises the key research outcomes in the area of nano robotics, stressing on magnetic control of nano robots.

2 Nano Robots

As the name suggests, these are robots with millimetres to several nanometer dimensions. It is practically impossible to mount the computing units, motors and propellers at this size. So the construction of these robots are extremely challenging and involves the knowledge of nano technology and materials. As the bodies without actuators, these depend extensively on external agents to drive. Magnetic propulsion is one of the widely used method to manoeuvre nano robots [5]. Few literatures have been found on quorum sensing and using chemical signalling to move the robots [1], but magnetic control seems to be relatively easier and widely used.

2.1 Structure of the Nano Robot

Nano robots are targeted for industrial and medical applications. These environments will have a low Reynolds number *Re* (Ratio of inertial force to viscous force). Hence the viscous force plays a predominant role and demand the robots to be designed in special shapes to overcome this effect. Spiral structure is one of the commonly used structures[8]. Micro organisms like bacteria are inspiration behind designing nano robots in spiral or helical shapes. Figure: (1) represents one such structures proposed by Ghosh and Fischer [3].

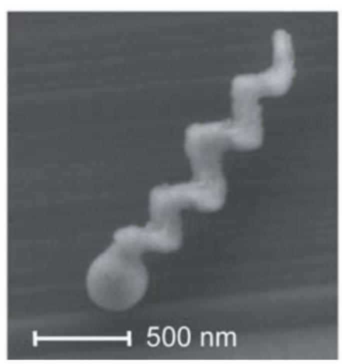

Figure 1: Spiral Structured Nano Robot (Image Courtesy: Ghosh and Fischer [3])

2.2 Fabrication of Nano Robot

There are several ways of fabricating nano robots. Choice of materials used and fabrication steps depends extensively on targeted applications. One of the methods, as explained by Matsumoto et al. [7], is to fabricate a Carbon Nano Coils (CNSs) coated with 2-methacryloyloxyethyl phosphorylcholine (MPC) polymer. These CNCs coated with MPC is biocompatible and not harmful to living cells. They use the Chemical Vapour Deposition (CVD) technique to fabricate the basic structure and coat it with thin layer of Cr and Ni (to add magnetic property) before a final coat with MPC. Figure 2 shows the steps involved in this process.

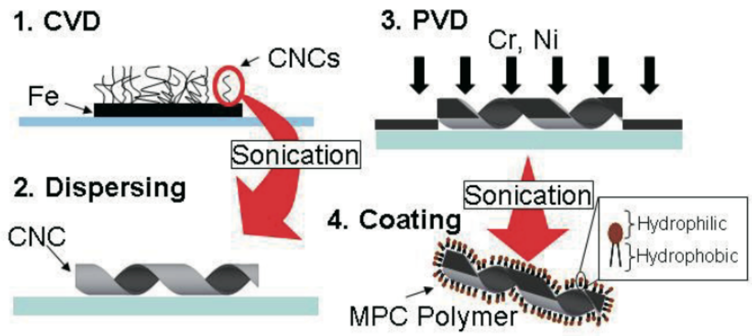

Figure 2: Fabrication steps in CNC Nano robot. (Image Courtesy: Matsumoto et al. [7])

3 Applications

Dimensions of Nano-Robots suits them perfectly for industrial and medical applications. Robots of the size of millimetres can be used in industrials valves for surveillance. Even smaller robots are best suited for medical applications. Robots fabricated by Matsumoto et al. [7] had a size of the order of $700nm$ ($700nm$ diameter, $250nm$ thickness and $350nm$ pitch) and Ghosh and Fischer [3] could also fabricate the robots of the similar size as mentioned in figure 1. Robots of this magnitude can be easily manoeuvred in the bodily fluids and controlled precisely for treating specific sites. Following are few examples.

3.1 Spinal Injury Treatment

Jonckheere and Lou [5] have proposed a novel idea of using nano robots for treatment of spinal injuries. They have proposed a method to detect the spinal injuries by nano robots coated with NO and Ca^{2+} nano sensors. Chemicals released at the spinal injuries have a special affinity towards NO and Ca^{2+} ions and this principle is used to design the nano sensors. A swarm of nano robots are employed to collectively help the injury detection and treatment. The robots have a magnetic material coating on them and can be controlled by external magnetic field. External system employs a soft X-ray microscope to detect the positions of individual robots inside the body. This information is then processed by a Digital Signal Processor (DSP) driving the magnetic coils to progressively guide the physical centre (centre of swarm of robots) towards the chemical centre (site of injury).

3.2 Cancer Treatment

Increasing rate of cancer has demanded extensive researches on treatments and therapies. Current infrastructures in medicine use chemotherapies and radiotherapies to treat the patients. An effective drug delivery system would obviously address the much needed necessity in this domain, while eliminating side effects of other methods. Durairaj et al. [2] have illustrated the use of nano robots for cancer treatment. Robots coated with bio sensors can be used to detect the exact locations of tumour and treat them.

3.3 Cardiology

Current state of the art cardiology institutes use stereotaxis Magnetic Navigation System (MNS) to increase the precision and safety in ablation procedures. In this method, catheters are coated with magnetic materials and are controlled by external magnetic fields. These catheters are used to deliver the drugs in required location, perform ablation procedures and 3D mapping of vascular structures. Nano robots can be used to perform all these tasks and can be guided through tortuous anatomy unreachable by manual navigation.

4 Control of Bio Nano Robots

Conventional robots use different type of actuators and sensors. Actuators like motors, combustion engines, hydraulic systems and springs are the most common ones. These actuators are coupled and controlled by central processor (may be onboard or may be external) to precisely control them. When it comes to scaling them down to the level of millimetre or lower, it becomes hard to choose the right actuators. In fact, engineers have to think of different mechanisms to steer the robots. As mentioned before in section 2, magnetic control is one of the widely used methods.

To control the robots magnetically, it has to be coated with magnetic substance like Ferrite (Fe), Nickel (Ni) or Chromium(IV) Oxide (CrO_2). These ferromagnetic materials have high susceptibility to the external magnetic field and and exhibit strong attraction to external fields. Advanced fabrication techniques today enables us to coat a thin layer of these materials uniformly on the nano structures. Following sections illustrate the details of controls of nano robots.

4.1 Control using magnetic coils

Honda et al. [4] have suggested propelling micro swimming particles using external magnetic fields in 1996. Since then, there has been significant research in this field and outcomes have proved that nano robots can be precisely controlled by external magnetic field. Theory behind this depends on basic Maxwell's equations (1).

$$\nabla . B = 0 \textit{(No Magnetic Monopoles)} \tag{1a}$$

$$\nabla . E = \rho \textit{(Gauss's Law)} \tag{1b}$$

$$\nabla \times E + \frac{\partial B}{\partial t} = 0 \textit{(Faraday's Law)} \tag{1c}$$

$$\nabla \times H = J + \frac{\partial D}{\partial t} \textit{(Ampere's Law)} \tag{1d}$$

Here E and B are electric and magnetic fields, J is the electric current density, ρ is the electric charge density. D and H corresponds to E and B through polarisation P and magnetisation M by following equations (2) and (3):

$$D = \epsilon_0 E + P = \epsilon P \tag{2}$$

$$H = \frac{B}{\mu_0} - M = \frac{B}{\mu} \tag{3}$$

where ϵ_0 and μ_0 are permittivity and permeability of vacuum, and ϵ and μ are permittivity and permeability of the material. Further, Biot-Savart's Law provides the calculation of magnetic field generated by gradient coil. Equation (4) represents Biot-Savart's law, where dl is the line element, r is the distance from the point.

$$dB = \frac{\mu_0}{4\pi} I \frac{dl \times r}{|r|^3} \tag{4}$$

Three gradient coils are used to generate a linear variation of z-component of magnetic field along the Cartesian axes x, y and z:

$$G_x = \frac{\partial B}{\partial x}; \qquad G_y = \frac{\partial B}{\partial y}; \qquad G_z = \frac{\partial B}{\partial z}; \tag{5}$$

Here G_x and G_y are called transverse gradients and G_z is called longitudinal gradient. We can use Helmholtz or Maxwell's coils to achieve this requirement. Resistance of the winding material and diameter of the coil are one of the many constraint parameters in designing the Helmholtz coils. Figure (3) is a demonstration of the experimental setup used by Zhang et al. [8]. By controlling the amplitude and phase of currents though Helmholtz coils, we can precisely generate the gradient fields required to direct the robots. The forward and backward movements of the robots is achieved by rotating magnetic fields. The magnetic head can rotate by applied magnetic field when the magnetic torque is greater than the viscous resistance of the fluid. An external control mechanism with a imaging subsystem and digital signal processor can be used to make a closed loop system to control the trajectory of the robot. Figure (4) shows the trajectory of the nano robot achieved by Matsumoto et al. [7] in 3.5mT field strength. A max speed of 0.45μm/s was observed in the experiment. Figure (5) is more impressive. Ghosh and Fischer [3] demonstrated this in a water medium, propelled by a external field of 6mT.

4.2 Control using MRI machines

Previous section introduces the techniques of controlling the nano robots with the external magnetic fields generating magnetic gradients in 3D. MRI (Magnetic Resonance Imaging) machines widely used in hospitals today have a mechanism to develop these fields. So, instead of constructing a new experimental setup to generate magnetic filed, why not use MRI machines to do it? Of course, these machines are extremely expensive and not be afforded individuals. But these are professionally built and can give a precise control of gradient fields generated. The permanent field of the MRI system magnetises the ferromagnetic material of the nano robot and an oscillating gradient is applied in the direction perpendicular to the direction of swimming. The resulting force in the direction of the gradient induces a drifting motion of the swimmer. As the swimmer gains a relative velocity with respect to the still fluid, the flow on the tail creates a lift force which propels the swimmer forward as depicted in Figure (6). For this experiment, Lalande et al. [6] used a tank of water as a medium and robots of 20-80mm tail length.

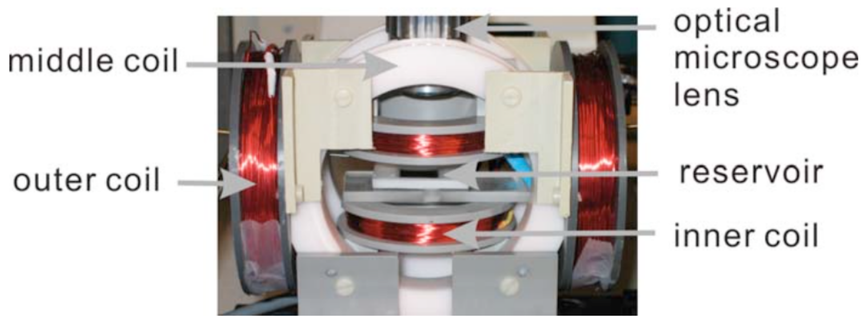

Figure 3: Experimental setup of X, Y and Z gradient coils. (Image Courtesy: Zhang et al. [8])

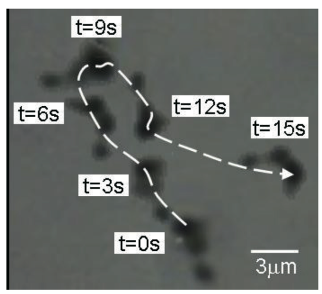

Figure 4: Nano robot trajectory achieved by Matsumoto et al. [7] (Image Courtesy: Matsumoto et al. [7])

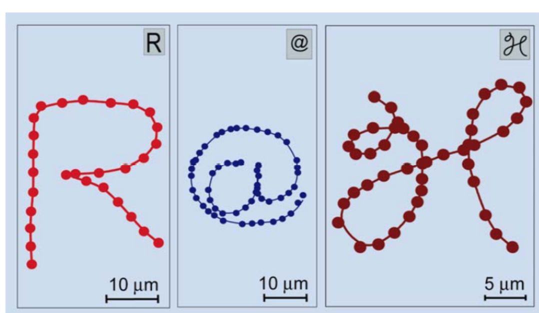

Figure 5: Trajectories of nano robot achieved by Ghosh and Fischer [3] in water medium. (Image Courtesy: Ghosh and Fischer [3])

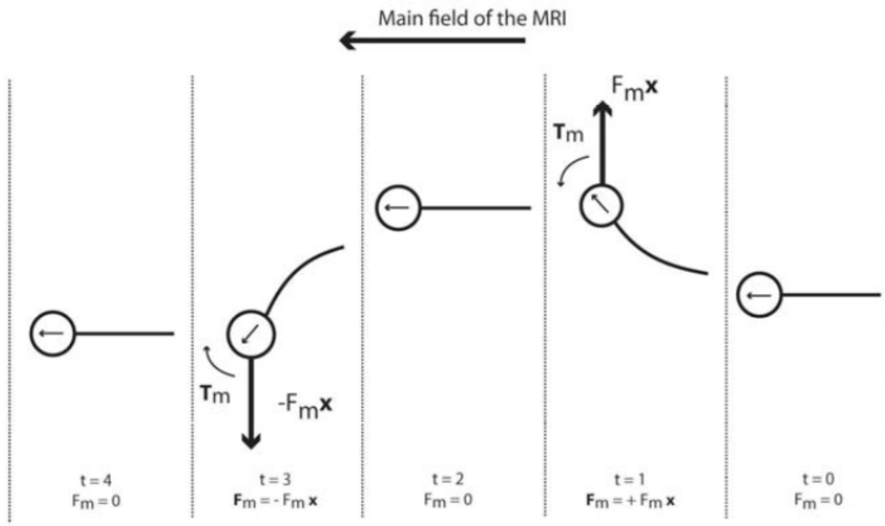

Figure 6: Representation of the behavior of the robot under the alternating field where Fm is the magnetic force produced by the alternating gradient, Tm is the torque induced by the anisotropy, and t is an arbitrary time. Arrows inside the ball represent the magnetisation direction. (Image Courtesy: Lalande et al. [6])

5 Conclusion

Nano robots, due to their size and controllability, are extremely helpful in medical applications. These can be effective in minimally invasive surgeries than current endoscopy and catheterism techniques. With computer aided control, doctors can achieve precision to the nano meter level and perform long duration surgeries with ease. With these host of benefits, construction and control of nano robots poses extreme challenges and needs innovation. Earlier sections have shown the basic theory behind the controlled propulsion of nano robot. Using MRI machines is a novel idea because it brings down the cost of building new devices to generate magnetic gradients. This report summaries the current state of the art features in the field of controlling nano robots. Future work is aimed at simulation of control system and proposing the control algorithms.

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