Tiny Robots, Massive Potential

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As nanotechnology has evolved from science-fiction to a fertile field of study in science and engineering, researchers have worked to translate macro-scale systems to the molecular level. An example of this is robotics, where efforts have been made to integrate nanosystem design and control to create useful technologies for a suite of applications. On the nanoscale, three major challenges related to design and control manifest: locomotion, manipulation and supplying power. These challenges can be addressed by adapting biomimetic solutions and utilizing these solutions in various applications.

Biomimetics

The dominant approach in designing nanorobots has been to mimic features observed in nature. Specifically, cells have been the starting point for a wide range of research relating to nanorobotic locomotion. Flagella are one such feature adapted for their robust performance at the nanoscale while still providing flexibility in terms of manufacturability and control [1]. Beyond mimicking nature, work has also been performed to integrate natural components with synthetic components. Martel *et al*. have shown progress in utilizing bacterial magnetosomes in conjunction with flagella nanomotors to manipulate micro-objects [2]. Furthermore, natural materials have been explored to ensure biocompatibility of nanorobots if introduced to the body, ensuring the immune system does not attack these therapeutic agents as threats [3].

Locomotion

Mimetic approaches are key to advancing nanorobotic locomotion because of the drastically different physics present at the nanoscale. In the macro-scale, inertial and gravity body forces dominate, with viscosity and surface tension considered secondarily (e.g., the prevalence of inviscid flow modeling). However, as the characteristic length decreases, intermolecular forces and Brownian motion become more significant, while body forces become negligible [4]. As a consequence, many of our macro-scale propulsion strategies, such as internal combustion or electric motors, would fail, if they could be mimicked at all. In addition, as previously stated, biomimetics has helped solving this problem by providing examples of flagellular propulsion and magnetotactic steering.

Flagellular locomotion is a result of the forces generated by a flagellum - a hair-like structure attached to the nanorobot - rotating in a viscous liquid. This rotation causes a net propulsive force on the robot, moving it forward in whatever direction it is pointed [5]. Magnetotactic steering allows for the direction of the nanorobot to be controlled by the alignment of magnetosomes (membrane-based iron nanoparticles) with an applied magnetic field - just like a compass. By externally manipulating this magnetic field, the nanorobot can be “steered” [6].

Beyond the mechanics of locomotion, strategies are needed to control the collective motion of a swarm of nanorobots effectively and efficiently to achieve goals cooperatively. Macro-scale control schemes have been explored for application in nanorobotic systems, including neural networks [7] and particle swarm optimization [8]. While simulations have been the primary means of assessing viability at this stage, some experimental testing has been performed [7].

Manipulation

Nanomanipulation has key applications in both manufacturing nanorobots and utilizing them to affect change in their environment. Technologies such as atomic force microscopy, previously used to observe nanoscale systems, have been explored as potential manipulators [9]. More broadly, nanorobot swarms have also been used to reconfigure micro-size blocks due to the force exerted by the robots pushing against them, as shown in Figure 1 [10].

Arguably, more important than the actual manipulation mechanism is the strategy for providing force feedback to the operator or nanorobot when performing a task. This is necessary to ensure its accurate movement and delicate handling of fragile components. Force feedback sensors have been successfully implemented and tested at the nanoscale, where a cantilever is coupled with a piezoresistive circuit to convert contact deformation into a force measurement [11]. Similar work has also been extrapolated into haptics research, where the rendering and stability of the controller operating between the human and nanomachine was studied and optimized [12].

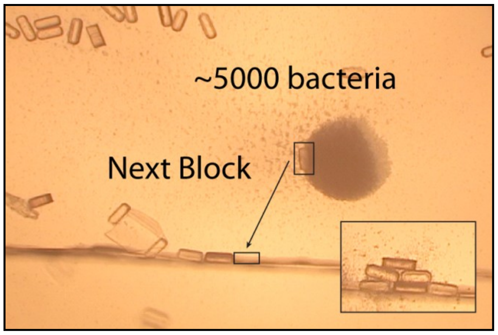

Figure 1 *Bacteria swarm controlled to manipulate blocks into a pyramid configuration [10]*

Supplying Power

To locomote, manipulate or perform any other function, the nanorobot must have a supply of power from some source, either externally provided to the system or inherent to the system design. One mode for supplying power to the system externally has been through electromagnetic radiation, such as visible light, similar to how a plant absorbs sunlight and stores it in ATP (adenosine triphosphate). A design for a motorized nanocar has been proposed (shown in Figure 2) where light will excite a bond in the vehicle's design to force a paddlewheel-like operation of a portion of the molecule [13]. A second externally powered mode of operation was previously described regarding magnetosomes and magnetic field manipulation for steering.

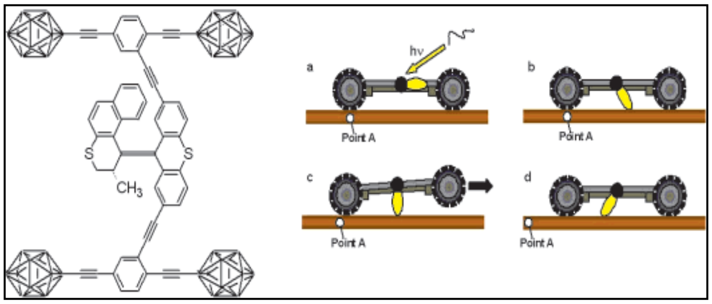

Figure 2 *"Motorized" nanocar chemical structure and locomotive mode [13]*

Internal powering has been accomplished through chemical reactions and by piezoelectric materials. For chemical powering, research has been performed on the feasibility of harvesting energy from glucose by nanorobots travelling in the bloodstream [14]. For piezo-based power supplies, piezo arrays have been analyzed numerically for their ability to convert mechanical vibrations and ultrasonic waves into power for a nanosystem, using power processing built into the design of the generator [15].

Applications

Beyond the generalized research being performed in terms of system design and control, specialized research into specific applications is being carried out. Nanomedicine is by far the most prevalent and promising potential application, which is opening up new avenues for diagnosis and treatment currently unavailable [16]. Specific applications include vascular surgery, targeted destruction of cancerous cells and treating brain aneurisms [17, 18]. The entry of a nanorobot into a capillary near a neuron is shown in Figure 3. Because of the nano-length-scale of these devices, they are able to pass through certain areas of the body, such as the blood-brain barrier, previously inaccessible to most treatments.

Though not explored to the same depth as nanomedicine, additional applications under consideration for nanorobotics include environmental monitoring [12], data storage [19], and space exploration [20]. Where nanomedicine is primarily concerned with creating new treatments and tools, nano-related advances in these other fields focus on providing greater efficiency (e.g., reducing the weight of payload travelling to space).

Potential Problems

The utilization of nanorobots presents significant new challenges in terms of safety. With nanomedicine being the largest target for implementation, an assessment of potential problems associated with introducing nanorobot to the body is appropriate. Cytotoxicity is a prevalent concern; any robot introduced to the body should be extensively tested for undesired effects not just in the cells it is targeting, but all it may come in contact with. Cytotoxicity has been addressed in relation to other nanomaterials [21], and the complexity associated with nanorobots will only amplify the potential for this problem.

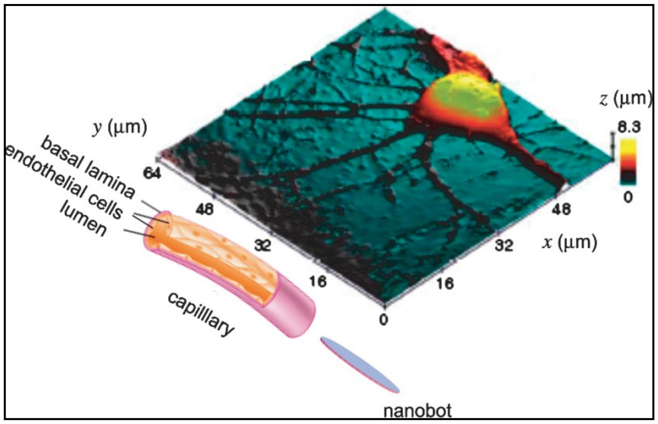

Figure 3 *Size and shape requirements for a nanorobot operating in a capillary near a neuron [3]*

Conclusion

Although the ubiquity of nanorobots is still decades away, advances are continually being made to bring us closer to that day. Advances in system design and control will allow us to adapt our knowledge to the nano-scale, and advances in manufacturing will allow us to implement these novel adaptations. These will revolutionize how we study ourselves and the world around us.

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