Abstract:

Two main areas have been identified in nanorobotics. The first is the design and simulation of nanodevices, based largely on aspects of macro-scale robots including power, communication, and navigation. The second, which has had more work done in it, involves the assembly of nanorobots through self-assembly or manipulation at the nano-scale. Techniques for this include the already proven use of microscopy equipment for manipulation. Current design of nanorobots is based on those already existing in biological systems. As such, the majority of applications in this area are being directed towards medicine. Here, nanotechnology promises advantages such as versatility, superior building materials, and reliability.

Background and Introduction:

The emerging field of nanorobotics deals with both the design of nano-scale machines and the controlled manipulation of nano-sized objects. Work in this area is still largely theoretical, and no artificial non-biological nanorobots have yet been built.

Medical technology will be the first application to reap the benefits of nanorobot applications. As such, a majority of the nanorobots currently being developed are designed to perform specific tasks at the molecular level. These may include molecular manufacturing of circuits, machines, and devices as well as self-replication to replace
worn-out components. Nanorobots lie at the heart of many proposed solutions of nanomedicine, of which applications include serving as antibodies in weak immune systems, curing diseases unresponsive to conventional methods, repairing damaged tissue, unblocking arteries affected by plaque, construction of replacement body organs, and more. One example, currently being explored at the Ecole Polytechnique Montreal, is developing a nanorobot capable of targeted drug delivery.

A major advantage that nanorobots provide is durability, as theoretically they could last for years. Their operation time would also be much lower because their displacements are smaller, allowing for the same speed of events to happen across a smaller time. The doors opened by the special attributes present in nanoscale activity, reduced material cost, and accessibility to previously unreachable areas are motivating further research in nanorobotics. Even though a large majority of the work done in this field has been thus far theoretical, the facts discovered by testing of primitive devices and their potential applications promise that chemists, physicists, engineers, medical researchers, as well as health patients will reap benefits.

My personal interest in this field stems from a summer research internship involving silver nanoparticles to be used for antibacterial purposes in wound healing. I decided here to investigate a different facet of nanotechnology’s role in medicine, and because the undergraduate research work I am conducting at OSU relates to controls and robotics, nanorobotics and its role in medicine presented itself as an interesting area to gain a better understanding of. This combination of two areas that I have briefly worked in, may even prove to be something I choose to pursue in graduate research studies.
**Literature Review:**

Research in nanorobotics began in the late 1980’s. Around this time, Drexler published his research on nanosystems, in which he discusses a field that derives largely from the field of macroscopic robots. From there, research developed along two paths: design and simulation of robots with nanoscale dimensions, and manipulation/assembly of nanoscale components with macroscopic instruments¹.

Even though artificial nanorobots do not yet exist, biological nanorobotic systems do, proving that such systems are possible. As such, most of the research done along this first path of design and simulation has been done in the context of medicine², and shown that this field also serves to derive from biological systems. The first nanomedical device design technical paper was published in 1998³, and current research on the medical implications of molecular nanotechnology has been collected into one source, which is commonly referenced in medicinal applications of nanorobots⁴. While robotics has been used in health care for awhile, the nano aspect of this only recently surfaced in this area. In fact, it didn’t even appear in the comprehensive review of robotics in health care in 1993⁵.

As research progresses in design, mechanical components such as nano-sized gears, such as that seen in Figure 1, built out of carbon atoms in a diamondoid structure are being constructed. Details of their use in medicine, such as size, amount, effect on
environment, etc. were outlined in a comprehensive paper\textsuperscript{6}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{nanogear.png}
\caption{Detail of nanogear in a theoretical nanorobot.\textsuperscript{6}}
\end{figure}

The other area of focus is on the actual assembly of the systems, which investigates the precise interactions with nanoscale objects or manipulation with nanoscale resolution. Because of nanotechnology’s rapid growth, there has been a great need for practical techniques to manipulate and assembly nanodevices. Subsequently, a larger number of papers exist in this topic than the first area mentioned. Development of these methods is still in a beginning stage, and the chemical and physical reasons behind them are not yet fully understood\textsuperscript{7}. One of the first demonstrations was done at Bell Labs, where nano germanium structures were created on a germanium surface by raising the voltage bias of an STM tip\textsuperscript{8,9}.

Most recent literature in this field investigates new solutions for problems not yet discussed, but developing off of techqiues used in macro-robotics and biological systems.
Theoretical Background:

Research in the design side of nanorobotics has determined information about their properties that will affect their use in medicinal applications. This has been accomplished by viewing the human body from a molecular standpoint, which provides a better understanding of what is required of nanomachines in that environment. Nanotechnology seeks to correct problems that may occur by mimicking natural machines, which may be damaged. They may also serve as a supplement to something such as the immune system.

One such fact, important to medicinal applications, is the determination that carbon is an excellent candidate for use due its strength and chemical inertness, however additional elements are also being considered. Relating these instruments to the human body, it was decided that various sizes and shapes of nanorobots are possible and should be tested for use in various parts of the body. For example, a nanorobot working in tissue could be as large as 50-100 microns, whereas one in the bloodstream needs to be 500-3000 nm. Injection of a dose of 3 cm$^3$ would be acceptable for the human body, since it has an average blood volume of 5400 cm$^3$.

Another area to address is how the nanorobots are powered in the body. Some suggest that power be supplied by glucose and oxygen already present in the body. Alternately, external acoustic power could be supplied. Some believe that energy storage devices are a necessary supplementary supply. This will be an important area to further research, as onboard volume on the robots is limited.

Acoustic signals sent back and forth between the nanorobot and the external source could theoretically provide steady communication. Communication will be
necessary at least between nanorobots to pass sensory and control data for ensuring correct operation and monitoring progress. It will most likely also be used to transmit information to a human patient and medical personnel.

The way that the immune system will react to the presence of these devices is also being investigated. Since the immune system will attack any foreign objects present, it is proposed that the nanorobots be made with smooth, flawless, diamond surfaces. Experimental studies show that diamond exteriors may be ideal, because less leukocyte activity and fibrinogen adsorption occurs with these chemically inert surfaces.⁴

Another aspect for consideration is the shape of the device. While biological nanorobots can move freely with respect to one another, mechanical components are supported by stiff housing. Flexibility would make it much easier for the device to enter the cytoplasm, affect microhydrodynamic stability, and more.⁵

Two methods of navigation are currently being considered: positional-where the nanorobot knows its place in the body, and functional-where the nanorobot detects subtle variations in the environment to compare to a set of predefined conditions. Figure 2 provides an example of a proposed nanorobot searching for its path. Figure 3 is the same nanorobot avoiding obstacles, and Figure 4 displays a drug delivery to the desired organ inlet.
Figure 2. Nanorobot finding its path\textsuperscript{10}

Figure 3. Nanorobot avoiding obstacles\textsuperscript{10}
Nanotechnology, and therefore nanorobotics assembly, is being pursued along two directions: top-down and bottom-up. The top-down approach, which is the reduction of semiconductor fabrication techniques to smaller and smaller levels, has met with little success in this area, due to limitations in optical lithography techniques because the wavelength of visible light is 500 nm. The development of x-ray and electron beam lithography techniques will reduce sizes even further, but complexity and fabrication costs increase significantly. Because this field requires precise positioning of molecules and atoms, this direction has been mostly discarded in favor of bottom-up techniques, which involve assembling systems out of individual atoms and molecules.

Two methods are employed for this: self-assembly and nanomanipulation. Self-assembly is based on traditional chemistry and bulk-processing. However, it has proven to have severe limitations, because the structures tend to be highly symmetric and organic, making them non-robust and lacking mechanical strength. Nanomanipulation, which is based on controlled positioning of nanoscale objects using macroscopic instruments.
through direct application of forces and electric fields, has been more successful. Work in this area is especially focused on the use of Scanning Probe Microscopy to deposit or remove small amounts of material.

Scanning Tunneling Microscopy (STM) and Atomic Force Microscopy (AFM), which is the most common type, are both examples of Scanning Probe Microscopy. STM, whose principles are displayed in Figure 5, operates with a sharp conducting probe on a conductive sample. The quantum-mechanical effect of tunneling creates an electron flow across the gap between the tip and the sample. The current of this flow can be detected and used to keep a constant gap distance, by adjusting the tip through the use of piezoelectric actuators. By maintaining a constant distance, the tip is moved across a surface parallel to the sample, producing a terrain map with sample features.

Figure 5. Scanning Tunneling Microscope

![Figure 5. Scanning Tunneling Microscope](image-url)
The AFM operates on similar principles, using interatomic forces to deflect a cantilever with a tip, as shown in Figure 6. A laser beam measures the amount of deflection and servos are used to adjust the gap distance accordingly. Because this method does not require conductive samples or tip, it has a wider applicability.

![Diagram of Atomic Force Microscopy](image)

Figure 6. Atomic Force Microscopy

Contact mode utilizes repulsive forces to prevent the tip from entering the sample, and provides a high resolution result. However, delicate samples may be damaged by the contact forces with this method. Alternatively, the non-contact mode can be used, but provides a lower resolution. The tip is placed farther away from the sample and the tip vibrated at a frequency near the cantilever’s resonance frequency. As the force between the tip and sample, which is equal to the cantilever’s spring constant, changes, the resonance frequency is affected and accordingly adjusted using a feedback loop to maintain it at a constant value.

Manipulation of nano objects began by operating on the principle that the interaction between the tip and sample can create changes in the tip and/or the sample. From this starting point, the SPM started being modeled as a robot with three degrees of freedom (x, y, z) and a tip as a robotic hand. Motion, sensing, end effectors, and programming are some of the areas that have been researched. It was proven as early as
1998 that these methods are possible and effective. These methods are now commonly being used for multiple aspects of nanotechnology research.
Current Research and Applications:

Nanorobots are currently still in the development phase, as no non-biological ones have yet been created. Much of the design relies on comparison to macro-sized robots and the principles, on which they operate. Current work is being conducted on various operations, such as “pick and place”. The successful work to date in this area has involved transferring of atoms using STM\textsuperscript{12}.

Another operation is compliant motion, which is the most sophisticated operation in macrorobotics. This involves fine motions, accommodations and force control. The nanoscale analog of this has not been researched, though it is speculated that chemical affinity between molecules and atoms would be responsible for the compliance.\textsuperscript{11} This important aspect will prove vital to figure out so that applications of these nanorobots, including cell repair, tissue regeneration, and immune system backup, can come to realization.

Although some may picture nanorobots as devices in the body, which self-replicate for additional protection, many scientists believe that self-replication is unnecessary. While it would reduce costs, these researchers hold to the fact that a simpler device designed with a specific task would be more appropriate.\textsuperscript{5} Also, it would eliminate additional device complexity, reduce reliability, and possibly interfere with the main goal. If no self-replication is desired, then nanofactories may need to be developed for their manufacture.

On the assembly side of nanorobotics, current research attempts to model the SPM as a robot with three degrees of freedom. The vertical displacement of the SPM is controlled simply by a feedback loop using tunneling current or force. Accurate
horizontal motion is an area requiring more work, as it relies on calibration of the piezoelectric actuators, which often suffer from creep and hysteresis. In addition, thermal drift of the instrument is very significant. At room temperature a drift of one atomic diameter per second is common. Compensations for thermal drift have been attempted by operating the machine at very low temperatures. However, this introduces complex technology. Another complication is that the SPM must often operate in a liquid environment, especially in biological applications. Nanomanipulation in liquids is an area with little research completed in it.

One of the most exciting developments in the last five years for nanorobotics came with a new alternative for powering these devices. The catalytic activity of platinum coating on small gold rods was used to propel the rods. In a liquid solution, these rods continuously converted hydrogen peroxide to oxygen and water. Surface tension between the rod tip and the liquid was lowered due to the oxygen rich surroundings. The rod moved in the direction of the low surface tension region. Then, magnetized nickel stripes were added to the rods and controlled by an external magnetic field. So, with the use of a simple magnet, the direction of the rods was controlled.

The big question facing nanorobotics right now is how to successfully combine the necessary aspects of macro-mechanical robots and biological systems for a useful nanodevice. Several aspects of macro-sized robots still need to be worked out on the nanoscale, and alternatives for things such as flexibility seen on the biological level need to be developed.

The aforementioned project currently underway at the Ecole Polytechnique Montreal is a good representation of where the field stands technically, and provides
common examples of problems facing nanorobotics researchers. It proposes the use of a Magnetic Resonance Imaging (MRI) system as propulsion for the nanorobot in blood vessels, by using the MRI’s magnetic field to generate a magnetic force on the ferromagnetic material of the nanorobot. Challenges in making this a functional robot include regulating its evolution in the cardiovascular environment, real time control to monitor variations, and compensation for any image distortion caused by the ferromagnetic material. Like most work in the field, the project is currently gathering information to define design rules, and has the long term goal of completed development of a working prototype, further miniaturized to allow for entry to inaccessible regions.
**Future Directions:**

As this is a young field, present literature is relatively sparse and leaves much room for expansion of information. Specifically, the design of nanorobots needs more attention. Once the field advances enough to create a successful combination of biological characteristics and macrorobotic operations, nanorobots can start being produced, and testing can begin for their use in medicinal cases. The big goal is to provide solutions previously unavailable for healing, monitoring, and regeneration of the body.

Nanorobots hold promise for a strong presence in medicine to come. It proves essential when damage to the human body is highly selective, subtle, or time-critical. Their characteristics provide faster medical treatment, versatility, superior building materials, reliability, sensitive response threshold, minimum side effects, verification of progress, and precision.5

Since many objections to the feasibility of nanotechnology such as quantum mechanics, thermal motions and friction have been resolved13, nanorobots have a bright future. The Department of Defense health scientists issued a statement in 1997, which says that nanomedicine will play a major role by the year 2020, with initial applications focused in diagnostics and pharmaceutical manufacturing, and later proceeding into applications inside the body.16 Thanks to a recent increase in funding from the federal government, this looks to be a likely possibility.
References:


5 Robert A. Freitas Jr., Nanomedicine, Volume I: Basic Capabilities, Landes Bioscience, Georgetown, TX, 1999


7 Che Connie K., Gill Mark; Feb. 2000 *Nanomedicine: The Future of Healthcare*


10 Cavalcanti A., “Nanosystem Design with Dynamic Collision Detection for Autonomous Nanorobot Motion Control using Neural Networks” *Unpublished.*


12 Requicha, Aristides A.G., Laboratory for Molecular Robotics and Computer Science Department, University of Southern California, Los Angeles, CA 90089-0781 [http://www-lmr.usc.edu/~lmr](http://www-lmr.usc.edu/~lmr)


15 *Nanomotors Rev Up.*, By: Service, Robert F., Science Now, 1/7/2005

**Individual Statement:**

This course gave me a solid overview of nanotechnology. I had limited knowledge and experience in this field before I began this course and feel that I left it much more informed. My previous summer internship dealt with nanoparticles, and this course proved a nice supplement to show me the theory and principles behind the synthesis and self-assembly. I also really enjoyed using the various microscopy techniques to analyze our particles. This course also gave me more practice in writing journal-type papers, which will prove invaluable as I enter my graduate studies. Although I am not sure whether or not I want to specifically focus on nanotechnology in graduate school, this course has given me a much better understanding of where the field stands and applications it promises to unveil in the near future.

The one thing I would change about this course is the amount of work to do at the end of the semester. A lab report, presentation, and final paper is a lot to fit in over a span of a couple of weeks. There were a few weeks towards the beginning of the semester with no assignments. The course could possibly be condensed more so at the beginning so that the work load is spread more evenly.

Nanotechnology is the multidisciplinary study of particles, devices, and systems at the nanoscale. Their synthesis, self-assembly, and characterization are main areas of interest. Different, unexpected characteristics appear in some elements at this level that open doors for new applications. Also, research shows that operations at the nanoscale may prove quite useful in areas such as medicine and the environment. Much is yet unknown in this field, including exactly what the societal implications and technological advances include.
This course helped me view my own discipline as a much broader topic. This was my first chance at the university to work in a team of people not solely studying engineering. It helped me see new directions that work can be taken, and ways to apply knowledge learned in core engineering classes to different topics.