Chapter 1
Nanorobotics: Past, Present, and Future

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Abstract This chapter focuses on the state of the art in the field of nanorobotics by presenting a brief historical overview, the various types of nanorobotic systems, their applications, and future directions in this field. Nanorobots are basically any type of active structure capable of any one of the following (or any of their combination): actuation, sensing, manipulation, propulsion, signaling, information processing, intelligence, and swarm behavior at the nanoscale (10^{-9} m). The following four types of nanorobotic systems have been developed and studied so far (a) large size nanomanipulators with nanoscale manipulation capability; (b) protein- and DNA-based bionanorobotic systems; (c) magnetically guided nanorobotic systems; and (d) bacterial-based nanorobotics. Nanorobotic systems are expected to be used in many different areas that range from medical to environmental sensing to space and military applications. From precise drug delivery to repairing cells and fighting tumor cells, nanorobots are expected to revolutionize the medical industry in the future.

1.1 Overview and Brief History of Nanorobotics

Robotic devices able to perform tasks at the nanoscale (i.e., scale of a nanometer) are called "***NanoRobots***." A nanometer is a billionth of a meter, that is, about 1/80,000 of the diameter of a human hair, or ten times the diameter of a hydrogen atom.

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The size-related challenge is the ability to measure, manipulate, and assemble matter with features on the scale of 1–100 nm. The field of nanorobotics studies the design, manufacturing, programming, and control of nanorobotic systems. Nanorobots are also referred to as ***nanobots*** or ***nanites*** by some enthusiasts of the field, although these terms do not accurately represent the engineering aspects of the system.

Nanorobotics is a relatively new field that grew out of the merging of robotics and nanotechnology during the late 1990s and early 2000s. This came as a natural evolution of the microrobotics field that grew rapidly in the 1990s and of the nanotechnology field that exploded in the 2000s. The term *NanoRobot* started being used by the robotics community in the late 1990s. Some of the earliest appearances of the term occur (a) in 1998 in the paper by Requicha et al. that focused on *NanoRobotic Assembly* [1]; (b) in Sitti and Hashimoto's paper on *Tele-Nanorobotics* [2]; and (c) in 1999 in Freitas' book on *NanoMedicine* where one can find a nice historical presentation of the nanorobotic concept for medical applications [3]. Prior to 1998 we rarely meet the term nanorobot although the concept of a nanorobot has been clearly described by several researchers and was referred to as "molecular machine" or "nanomachine" or "cell repair machine" [4, 5].

Two of the pioneers in the nanorobotics field are Eric K. Drexler and Robert A. Freitas. Drexler described the concept of molecular machinery and molecular manufacturing [6–8] while Freitas developed in great detail the concept of medical nanorobotics [3, 9, 10]. Prior to late 1990s the limited amount of scientific work on nanorobotics was mostly focused on concept generation, design, and modeling. Thorough computational and experimental studies on nanorobotics started being published only after the late 1990s. Nowadays, the nanorobotics field keeps expanding and many laboratories around the world are focusing their activities on this topic.

As with the robotics field, nanorobotics became known to the large audience through science fiction movies, TV series, and books. For example, Isaac Asimov in his 1966 book "Fantastic Voyage" (following the completion of the science fiction movie with the same name at the same year) described a miniscule submarine able to travel through the human bloodstream [11] while Michael Crighton in 2002 in his popular book "Prey" introduced a swarm of intelligent nanorobots that threaten humankind [12]. Although the nanorobotic concept being described in these fiction stories is far from being close to what a nanorobot is or will be for the scientific community, it helped generate public interest in this topic which is very important for the future growth of the field.

The term *NanoRobot* is being used by the scientific community in the broadest possible way. This term basically includes any type of active structure capable of anyone of the following (or any of their combination): actuation, sensing, manipulation, propulsion, signaling, information processing, intelligence, and swarm behavior at the nanoscale. For example, the term nanorobot includes large-scale manipulators with nanoscale precision accuracy and manipulation capabilities and microscale robotic devices with at least one nanoscale component [13]. It also includes molecular machines that are based on biological entities such as

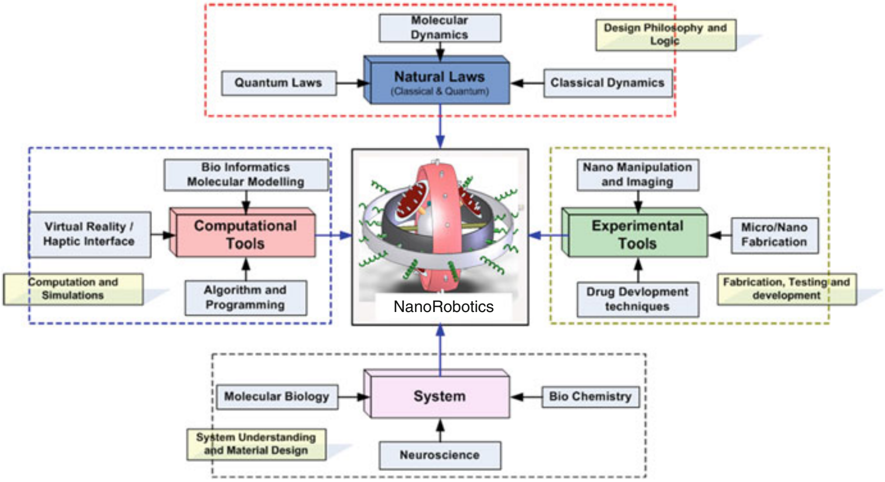


Fig. 1.1 Nanorobotics—a multidisciplinary field

proteins and DNA [14] and magnetic nanoparticles that can be guided by an external magnetic field [15].

In addition to the capabilities described above, in the future it is desirable that nanorobots have the following unique characteristic abilities associated with their nanoscale size and their presence in large numbers in a remote environment:

1. *Swarm intelligence* ([16, 17], Chaps. 3 and 17 of this book).
2. *Self-assembly and replication*—assemblage at the nanoscale and "*nanomaintenance*" [18, 19].
3. Nano- to macro-world *interface architecture*—an architecture enabling instant access to the nanorobots and its control and maintenance including haptics and virtual reality [20].

Nanorobotics is a field which calls for collaborative efforts between physicists, chemists, biologists, computer scientists, engineers, and other specialists to work towards this common objective as shown in Fig. 1.1 (this is just a representative figure and not exhaustive in nature).

Fully functional, autonomous nanorobots with completely artificial nanocomponents have not been realized yet. This is an open problem for the nanorobotics community that could easily be characterized as the "***Mount Everest of Nanorobotics***" paraphrasing Ferdinand Freudenstein who characterized in a similar way some important open kinematic problems of his time [21]. So far the nanorobotics community was able to develop large-scale manipulators with nanoscale precision and manipulation capability called nanomanipulators. The community was also able to demonstrate experimentally the development of several nanocomponents such as various types of nanostructures, nanosensors, nanomotors, nanocomputers, etc. that eventually could be used in the assembly of nanorobots. Finally, simple nanorobots based on molecular machines and nanoparticles have also been developed and successfully tested. We believe that the time is right to try to assemble the first ever fully functional and autonomous nanorobot.

1.2 Types of NanoRobotic Systems

In this section, we present the various types of nanorobotic devices that have been developed so far by scientists and engineers. These nanorobotic types are very different than the science fiction concept of nanorobots that are usually presented as nano-bugs as shown in Fig. 1.2 or such as the nanobots described in [22].

1.2.1 NanoManipulators

The first nanorobotic systems were not "nano" at all. Instead, they were large manipulator-like structures that had the capability of nanopositioning. The robotics community was not the first to get involved in the nanomanipulation field but was preceded and got inspired by the work of their colleagues from the physics and chemistry fields that used ***scanning probe microscopes*** (SPM) such as ***scanning tunneling microscopes*** (STM) and ***atomic force microscopes*** (AFM) to nanomanipulate atoms and molecules [23]. The first example of atom nanomanipulation using

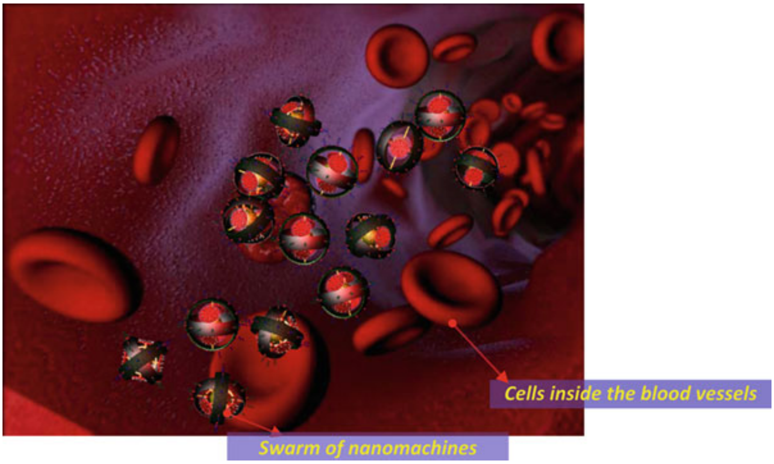


Fig. 1.2 Fictional concept of swarms of nanorobots inside the blood vessels. These nanomachines would detect and treat the effected cells. They would also deliver the targeted drug to the specific cells

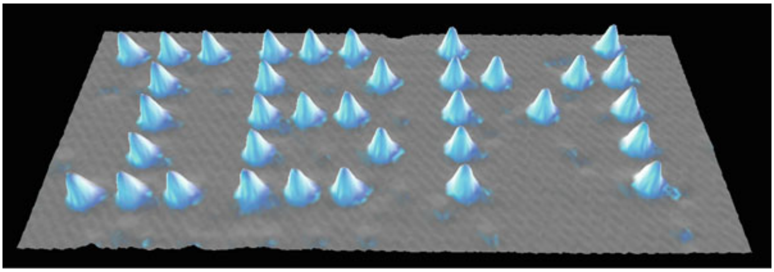


Fig. 1.3 STM manipulated zenon atoms form the word IBM [24] (image originally created by IBM Corporation, STM Image Gallery, http://www.almaden.ibm.com/vis/stm/library.html)

an STM was performed by Eigler and Schweizer in [24] where they nanopositioned 35 Zenon atoms to write the name of IBM, their employer (see Fig. 1.3).

As Requicha points out in one of the first reviews published on nanomanipulation from the robotics community in 1999 [25] initially a SPM is like a three degree-of-freedom (DOF) robotic manipulator, having *x*–*y*–*z* positioning capability at its tip but with no orientation capability. The manipulation capability of a SPM is based on the inter-atomic forces developed between the SPM's tip and the atoms to be manipulated. The SPM's tip serves as the manipulator end-effector and is the main nanocomponent of the nanomanipulator. At that time, there was no possibility for direct feedback for the SPM's tip positioning while the task is performed so the SPM played a dual role of manipulator and sensor at the nanoscale. Requicha in his prophetic review of 1999 describes a number of research topics that should be studied by the robotics community to improve the state of the art of nanomanipulation. For example, Requicha describes the needs for (a) developing 6 DOF nanomanipulators; (b) providing real-time feedback from the task space while the nanomanipulator is performing the task; (c) developing nanogrippers; (d) performing nanomanipulation tasks in liquid environments; (e) enhancing SPM's performance by the development of clever nanomanipulation strategies; (f) coupling of SPM manipulation with self-assembly properties for building nanostructures, etc. Since then, all these topics have been studied thoroughly by the robotics community in the context of nanomanipulation.

As the robotics community was getting more and more involved in the nanomanipulation field, we have observed the development of new nanorobotic manipulation systems that presented more capabilities, similar to those that are met in industrial manipulators. These new systems that are called nanorobotic manipulators (NRM) present higher number of DOFs at their end-effectors, higher end-effector dexterity, higher positioning accuracy, and higher end-effector tool possibilities. To increase positioning accuracy of the NRM and to improve the efficiency of its control and planning algorithms, NRMs were placed inside electron microscopes, such as scanning electron microscopes (SEMs) and transmission electron microscopes (TEMs). One of the first multi-degree-of-freedom NRMs was developed by

Fig. 1.4 DCG Systems' nProber Solution (http://www.dcgsystems.com). Eight probe nanomanipulator encoded positioners may be placed with 2nm resolution probe steps. The XYZ encoded center stage provides step and repeat capability, while allowing the probes to remain in registration while the sample is moved to the next bit (published with permission from DCG Systems, Inc., http://www.dcgsystems.com)

Dong, Arai, and Fukuda in 2001 where they demonstrated successful operation of a 10-DOF NRM system [26]. They then developed a 16-DOF NRM system [27] equipped with a SEM for real-time imaging of the manipulation task and a nanofabrication system based on electron-beam-induced deposition [28].

Nowadays, multi-DOF NRM systems are commercially available. Examples are the DCG Systems NanoManipulators (formerly the Zyvex NanoManipulators; http://www.dcgsystems.com/product.line.NI.html) shown in Fig. 1.4 and the Klocke Nanotechnik nanorobotic systems (http://www.nanomotor.de/m_nanorobotics.htm).

During the last 10 years, there have been several review papers that covered in great detail the subjects of *NanoManipulation* and *NanoRobotic Manipulators* [13, 29–31] including Chaps. 2, 7–12 of this book. The reader is referred to these papers and chapters for further information on this topic.

1.2.2 BioNanorobotics (DNA- and Protein-Based NanoRobotic Systems)

During the same period that nanorobotic manipulators were developed and studied, a second type of nanorobotic system, that of ***BioNanorobotics***, appeared and grew independently of the first. The term bionanorobotics, that was first introduced in 2003 [32, 33], denotes all nanorobotic systems that include nanocomponents that are based on biological elements such as proteins and DNA. Bionanorobotic systems are different than medical nanorobots in that even though bionanorobotic systems include components based on biological elements they may not be used in medical applications. Bionanorobotics is a subset of a more general field that of molecular machines and machine components that grew rapidly during the last decades [34].

The main goal in the field of bionanorobotics is to use various biological elements—whose function at the cellular level creates motion, force, or a signal—as nanorobotic components. These components perform their preprogrammed biological function in response to the specific physiochemical stimuli but in an artificial setting. In this way, proteins and DNA could act as motors, mechanical joints, transmission elements, or sensors. If all these different components were assembled together in the proper proportion and orientation they would form nanorobotic devices with multiple degrees of freedom, able to apply forces and manipulate objects in the nanoscale world. The advantage of using nature's machine components is that they are highly efficient and reliable. Just as conventional macro-robotic systems are used to generate forces and motions to accomplish specific tasks, bionanorobots could be used to manipulate nano-objects; to assemble and fabricate other machines or products; to perform maintenance, repair, and inspection operations. Figure 1.5 shows one such concept of a bionanorobot, with its "feet" made of helical peptides and its body using carbon nanotubes while the power unit is a biomolecular motor.

A plethora of molecular machines and machine components that could be used in nanorobotics has already been developed by scientists coming from the fields of physics, chemistry, biology, chemical and biomedical engineering [14, 19, 34]. Some very well-known examples are (a) the work of Ned Seeman's group in DNA-based nanomachine components including the development of a DNA bipedal walking device [35]; (b) the work of Carlo Montemagno's group that developed several protein-based nanomotors that rely on an energy-rich molecule known as adenosine triphosphate (ATP) [36, 37]; (c) Yurke et al. DNA-based nanotweezers [38]; and (d) the recent DNA-based nanorobot, shown in Fig. 1.6, for payload transport and delivery to cells by George Church's group [39]. Although these bionanorobots and components are important scientific achievements, all of them are lacking one major factor: the robotics science and engineering in their design, fabrication, control, and planning.

In an effort to bridge the gap between physicists, chemists, and biologists developing bionanorobotic systems and components on one side and the robotics community on the other, Dinos Mavroidis' group in US and Antoine Ferreira's group

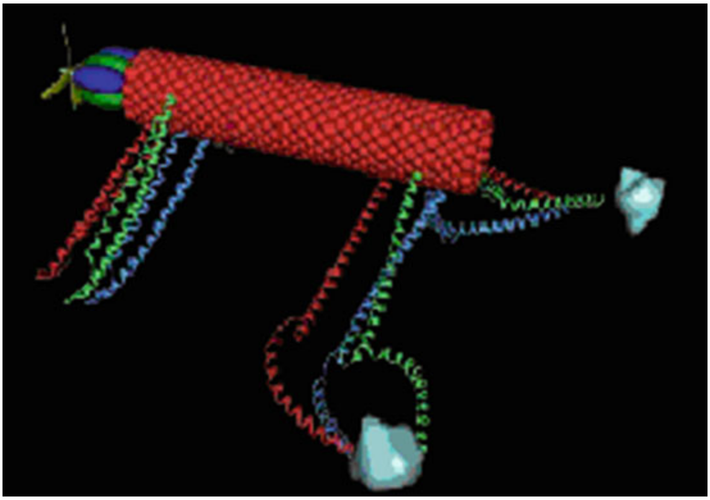


Fig. 1.5 Biological elements will be used to fabricate robotic systems. A vision of a bio-nanorobotic organism: carbon nanotubes form the main body; peptide limbs can be used for locomotion and object manipulation; a biomolecular motor located at the head can propel the device in various environments

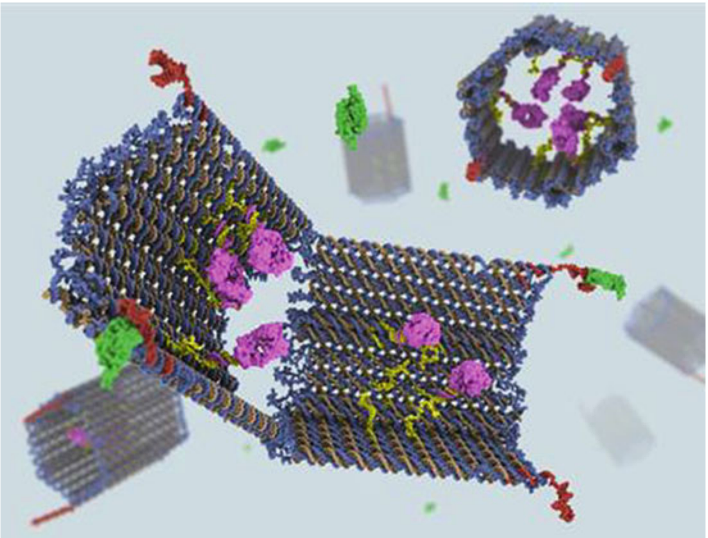


Fig. 1.6 CAD drawing of DNA nanorobots carrying protein-based payloads for targeted drug delivery [39] (published with permission from George Church)

in France proposed several new bionanorobots based on a bottom-up approach inspired by equivalent approaches in the macro-robotics field [40]. The Mavroidis' group focused on two different protein-based nanomotors: (a) a viral-based linear nanomotor called VPL [41] and (b) a protein-based nanogripper [42–44]. For the latter experimental validation was presented in [45]. More details about these two protein-based nanomotors could be found in Chap. 21 of this book. Ferreira's group focused more on the design, modeling, and virtual reality problems of bionanorobotic systems [46–49].

To complete successfully the activities described above, virtual prototyping tools based on molecular dynamics (MD) simulators had to be developed in order to understand the protein molecular mechanics and to develop dynamic and kinematic models to study the bionano-system performance and control aspects. The ability to visualize the atom-to-atom interaction in real time and observe the results in a fully immersive 3D environment was an additional feature of such simulations [46–49]. Virtual reality (VR) technology was applied in these MD simulators, which not only provided immersive visualization but also gave an added functionality of CAD-based design, simulation, navigation, and interactive manipulation of molecular biological components. The simulation system shown in Fig. 1.7 allows manipulation, connection, and assembly of bio-nanorobotic components in molecular dynamic simulations using real-time VR devices such as stereo glasses, 3D trackers, force-feedback devices, and 3D graphical display.

Research in the field of bionanorobotic system continues. However, it is clear that there is still a lot more that needs to be done in order to bring together the two scientific communities involved with the development of bionanorobotics. Additional information about this topic could be found in Chaps. 18, 19, and 21 of this book and in [50].

1.2.3 Magnetically Guided NanoRobotic Systems

The third type of nanorobotic system developed so far is much simpler than the previous two types but closer to the concept of a full nanoscale robotic system as the one shown in Fig. 1.2 in the sense that its dimensions are at the nanoscale and it is composed of artificial nanocomponents. This nanorobot is basically a simple nanoparticle comprising a ferromagnetic material. The obvious question of course is, "how can a nanoparticle be considered as a nanorobot?" The answer to this is that all components and functions that constitute a robotic system have been moved outside of the robot structure. Actuation and propulsion could be achieved using an external magnetic field and its gradients that could apply a six degree-of-freedom magnetic force on the nanoparticle(s) (see Fig. 1.8). Sensing and tracking of the nanoparticle motion could be done using external imaging modalities such as microscopes or magnetic resonance imaging (MRI) scanners (see Fig. 1.8). Once the actuation and sensing has been achieved using the external magnetic field and imaging modalities then it is possible to implement a closed loop control algorithm as shown in Fig. 1.8 that will guide the nanoparticle/nanorobot at the desired location. A nice literature review on this topic can be found in [51].

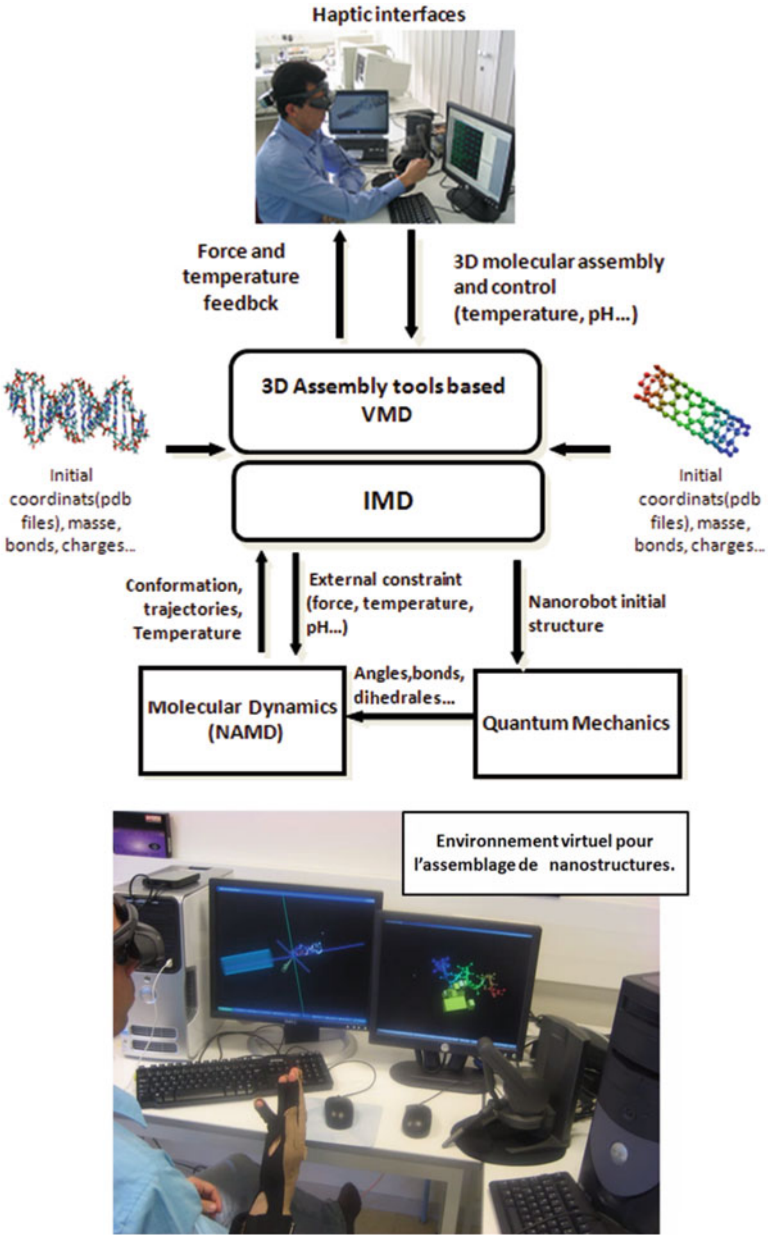


Fig. 1.7 *Top*: Basic concept of virtual environment and haptics technology coupled to multi-physics computational methods for drug delivery nanovector simulation. *Bottom*: Experimental interactive simulation platform using virtual reality interfaces. In the virtual molecular dynamics (VMD) environment, the user applies forces to simulated bio-nanorobotic structures via a force-feedback haptic interface while manipulation is performed through a virtual hand. The headtracker is mounted on a pair of shutter glasses for operator immersion

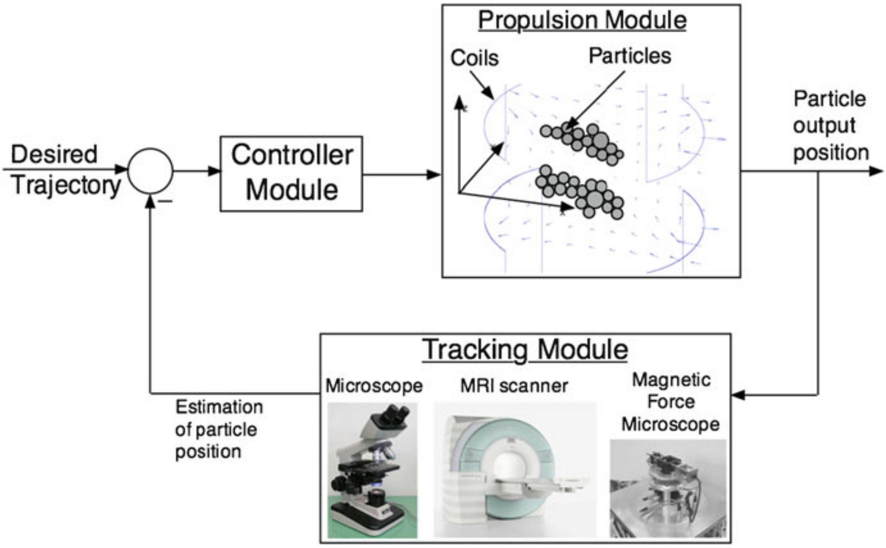


Fig. 1.8 General concept of closed-loop system for propulsion and guidance of magnetically driven nanoparticles using external magnetic fields and imaging modalities (published with permission from Panagiotis Vartholomeos)

Research in this field has been pioneered since 2003 by Sylvain Martel at the Ecole Polytechnique de Montréal [52–55]. He has used clinical MRI to navigate an inflow of 10.9-μm magnetic microparticles into a branch of a Y-shaped microchannel [54] and was the first to perform in vivo experiments on a living animal where he demonstrated propulsion and navigation of an untethered device in the blood vessel [55]. His analytical and experimental research results have been limited to millimeter- and micrometer-sized nonfunctionalized magnetic particles.

A systematic approach towards MRI-based guidance of nanoscale functionalized robotic capsules began for the first time, in the summer of 2008 in the context of the European Project NANOMA. Researchers of the NANOMA team have successfully developed a process for producing agglomerates of ferromagnetic filled multi-walled carbon nanotubes (FMWCNT) that were able to be steered in a MRI system. Their process is capable of producing vertically aligned multi-walled carbon nanotubes filled with high aspect ratio *nickel* (Ni), *iron* (Fe), and *cobalt* (Co) with a sufficient magnetic susceptibility artifact [56, 57] to be detected by the MRI modality. The direction and magnitude of the forces that are applied on the magnetic microparticles are generated according to a control law, where the feedback (i.e., the endovascular position of the microparticles) is calculated by the processing of the MRI data [58, 59]. Navigation techniques in combination with appropriate chemical modification of the nanoparticles' surfaces yield a more localized and controlled treatment as well as controlled drug-release mechanisms [60].

One of the limitations of MRI scanners for being used in the guidance of magnetic nanoparticles is the generation of weak magnetic gradients that are much smaller than those required to produce adequate propulsion forces that can move and guide the nanorobots at the nanoscale [51]. One way to resolve this challenge is to develop specially designed electromagnetic systems that can generate strong external magnetic fields with high magnetic gradients that can be used in the manipulation of magnetic nanoparticles at the nanoscale. Towards this goal, a five degree-of-freedom electromagnetic manipulator has been developed in Brad Nelson's laboratory [61] that in its newer version can steer and control magnetic drug delivery nanoagents [62].

Research in this field is currently showing a rapid expansion. The reader may find additional information regarding magnetically guided nanorobots in Chaps. 13–15 of this book.

1.2.4 Bacterial-Based Nanorobotics

The fourth type of nanorobotic system that exists today is based on the way that bacteria move in a fluidic environment [63]. This is a "biomimetic" type of nanorobot as it uses systems or concepts developed by nature but it is also a very "unusual" type of nanorobot from an engineering point of view. The bacterial-based nanorobotic systems and some of their versions could also be considered (depending on their fabrication technique and actuation) as either a bionanorobotic system or a magnetically guided nanorobotic system as presented earlier. However, because of the uniqueness in their design, control, and guidance we consider them to be an independent type of nanorobotic system.

Unicellular organisms such as *E. coli* and other bacteria have an interesting mode of motility [64, 65]. They have a number of molecular motors, about 45nm in diameter, that drive their "feet" or the flagella that help the cell to swim. Motility is critical for cells, as they often have to travel from a less favorable to a more favorable environment. The flagella are helical filaments that extend out of the cell into the medium and perform a function analogous to what the oars perform to a boat. The flagella and the motor assembly are called a flagellum. The flagella motors impart a rotary motion into the flagella [66]. The flagella motors allow the bacteria to move at speeds that can reach 25 μm/s while their torque output could range from 2,700 to 4,600 pN-nm making them one of the most powerful nanomotors found in nature.

There are two different approaches in developing bacterial-based nanorobotic systems. The first approach is using living bacteria to serve as the nanorobotic system that will move in the fluidic environment and manipulate objects in it. The other approach is developing fully artificial bacteria-like nanorobots that are powered using an external magnetic field.

The first approach is trying to take advantage of the biological engineering already in place in living bacteria and most importantly their propulsion capability through their flagella motors. From the robotics point of view, the goal is to use

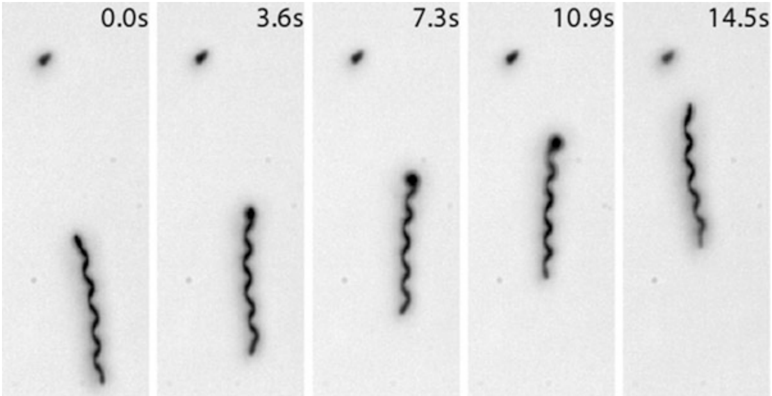


Fig. 1.9 Artificial bacterial microswimmers developed at ETH Zurich. By adjusting the rotating speed and direction of the external magnetic field, velocity and direction of the motion of the helical swimmers can be tuned in a controlled fashion (published with permission from B.J. Nelson, ETH Zurich, http://www.iris.ethz.ch/)

a team of bacteria to move forward a small object (e.g., a tiny bead) in a fluidic environment and be able to control this process, i.e., control the speed, direction, amount of displacement, and on demand stop and resume of this process. So far it was shown that bacteria can move a micro-object in a random, i.e., uncontrolled direction [67] while the stop and resume phases of this process could be controlled either by light [68] or chemically [69, 70].

A special type of bacteria called magnetotactic bacteria (MTB) offer more possibilities for manipulation of objects at the micro and nanoscale. MTB are bacteria that possess magnetic nanoparticles on their membrane. A direct result of this is that their main functional characteristic is magnetotaxis, i.e., they can orient along the Earth's geomagnetic field lines [71]. Using the naturally embedded magnetic nanoparticles of MTBs, it was shown that well-controlled manipulation of micro-objects could be performed by MTBs once an external magnetic field is used to generate a torque for MTB steering control [72, 73].

The second approach in developing bacterial-based nanorobotic systems is a biomimetic one, i.e., the goal is to create completely artificial nanoswimmers by copying nature's design from bacteria. Inspired by the motion of spermatozoa, Dreyfus et al. [74] developed a microswimmer consisting of a thin paramagnetic filament that attached itself to a blood cell. By applying an oscillating magnetic field the swimmer propelled the cell through continuous deformation of the filament in a manner somewhat similar to a eukaryotic flagellum. Recent examples of artificial flagellum in the form of a nanocoil that has been propelled using a rotating magnetic field have been proposed by Brad Nelson's group [75] (see Fig. 1.9). The self-scrolling fabrication technique to fabricate helical swimmers of a size comparable to *E. coli* which are capable of swimming in both water and paraffin oil [76] has recently been performed as well by the same group.

It is clear that a lot needs to be done in this area of nanorobotics. Most of the work that has been done so far is still in a preliminary phase and the systems that have been developed are far from being ready to be used in a real application. The reader may refer to Chaps. 14, 16, and 20 for more detailed presentation on bacterial nanorobots.

1.3 Applications of NanoRobotic Systems

One of the more frequent questions that a nanorobotic engineer or researcher has to answer is the following: "Where nanorobotic systems could be used commercially and how soon could a nanorobotic product be on the market?" This is a very important question and a very difficult to respond if we have to be realistic.

In general, nanorobotic systems are expected to be used in many different areas. Their possible uses range from medical to environmental sensing to space and military applications. Molecular construction of complex devices could be possible by nanorobots of the future. From precise drug delivery to repairing cells and fighting tumor cells, nanorobots are expected to revolutionize the medical industry in the future [3, 9].

All these potential, future applications of nanorobotic systems stay mostly in the area of "science fiction" for the time being as a lot of basic research still needs to be performed. An exception is the large size nanomanipulator type of nanorobotic systems where, as we described earlier in this chapter, several commercially available models exist. However, strictly speaking, true nanoscale size robotic systems developed so far are at a very preliminary phase of their development, and their commercial use is many years away.

One indication for the present lack of commercialization of nanorobotic systems is the limited number of currently issued patents in this area. A simple search within US patents issued up to the moment when this chapter was being written revealed that only three patents exist that use the word "nanorobot" [77–79]. One of them issued in 2005 presents a nanomanipulator system [77] while the most recent ones (issued in 2011 and 2012) focus on nanoscale systems such as nanoelectronics for nanorobotics [78] and swarms of magnetically driven nanosensors for in situ spinal cord imaging [79]. We would also like to mention a recent patent by Sylvain Martel's group on MRI guided microrobots in a blood vessel, even if the systems covered by this patent are at the microscale [80]. In addition, there are many patent applications under consideration and it is expected that the number of patents issued in the area of nanorobotics will increase in the near future.

In general, nanorobotic systems should be used to perform tasks at the nanoscale that cannot be performed with other means, that are of high importance for humankind, and that present a significant business opportunity for future investors. In addition, the nanoscale environment could be considered as a remote, difficult to reach, and sometimes hazardous location for the humans and these site limitations add additional technical challenges for their successful deployment. Given these constraints, we foresee the following generic tasks at the nanoscale that nanorobotic systems should perform (a) in situ sensing; (b) manipulation of nano-objects; and (c) accurate nanopayload (e.g., drug) transportation and delivery.

In the rest of this section, we will try to present potential applications of nanorobotic systems that we believe are very promising for developing new commercial products in the years to come and for which there was substantial research activity recently. We would like to emphasize that we will not be exhaustive in our listing of applications but rather we will present the ones that we believe are the more promising at the moment for commercial use.

1.3.1 Medical Applications

Medicine has been a major application field for nanotechnology. In a similar way, medicine will be one of the most important applications areas for nanorobotics. Performing tasks inside the human body requires in many cases the use of nanosystems. For example, any task performed inside a cell will require nanoscale components. Furthermore, studies have shown that only objects 30–300nm in size can be circulated through the thinnest sections of the vasculature system. Therefore, nanorobotic systems will be needed to perform important tasks in these tiny locations inside the body.

One of the most representative medical tasks that nanorobots could perform is schematically shown in Fig. 1.10. This is the task of targeted drug delivery for localized therapy with improved efficiency and minimization of side effects. As shown in the figure, numerous nanorobotic agents carrying a drug for cancer therapy could be injected inside the body. The nanorobotic agents using their propulsion and guidance capabilities travel to the cancer location and deliver at that location only the drug that they are carrying. In a similar scenario, the nanorobotic agents could be equipped with nanosensors for in situ sensing and monitoring. A large number of technical papers have been written to describe how such a scenario (or similar scenarios for many other diseases that require targeted drug delivery) could become a reality [3, 9, 81–84].

There are several studies that tried to demonstrate experimentally the validity of the scenario described in Fig. 1.10. Most of the nanorobotic types presented earlier such as bionanorobotics, magnetically guided nanorobots, and bacterial-based nanorobotics have been developed for a medical application along the lines described above even if they are still at a preliminary development phase. We would like to highlight the application of nanorobotics in delivering a drug in the brain by bypassing the blood–brain barrier [85]. This is a very challenging task that cannot be performed with conventional ways and is an excellent example in medicine of where nanorobots are actually needed. Recently, intraocular microrobots have been employed for targeted drug delivery and for procedures such as retinal-vein cannulation that require a high degree of dexterity as shown in Fig. 1.11 [86, 87].

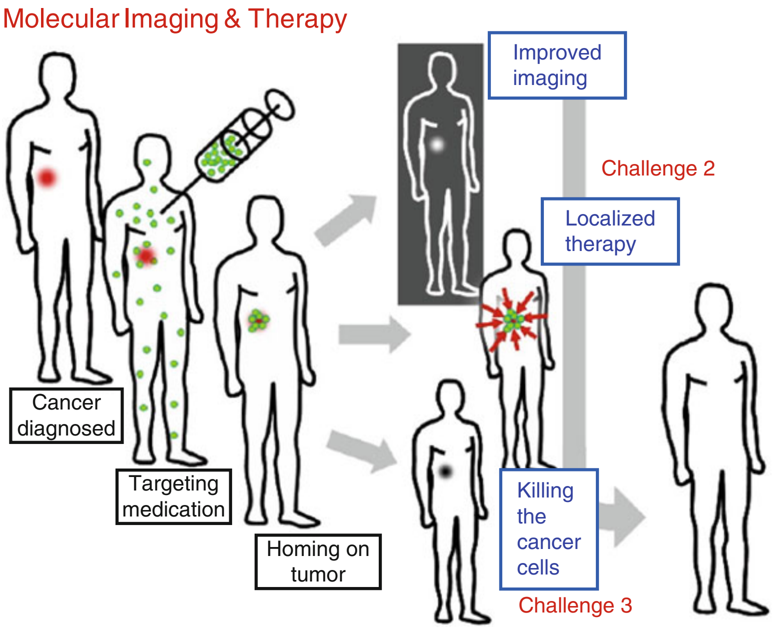
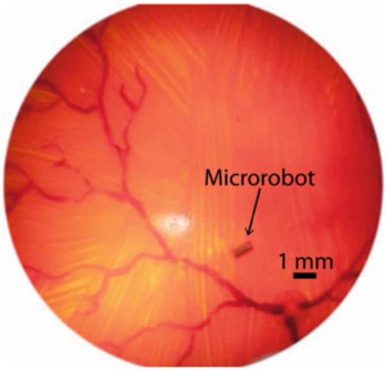


Fig. 1.10 Nanorobotics for targeted drug delivery (*Opensource Handbook of Nanoscience and Nanotechnology*)

Fig. 1.11 Intraocular microdevices for retinal-vein canulation, drug delivery, or oxygen sensing (published with permission from B.J. Nelson, ETH Zurich, http://www.iris.ethz.ch/)



It is clear that nanomedicine is a perfect application area for nanorobotics. We definitely expect commercial products in this area in the near future (even if this near future is at least a decade), most probably relevant to nanosensing and targeted drug delivery. Most of the chapters in this book discuss one way or other medical applications of nanorobots. Specifically Chaps. 10–21 are focused on medical applications.

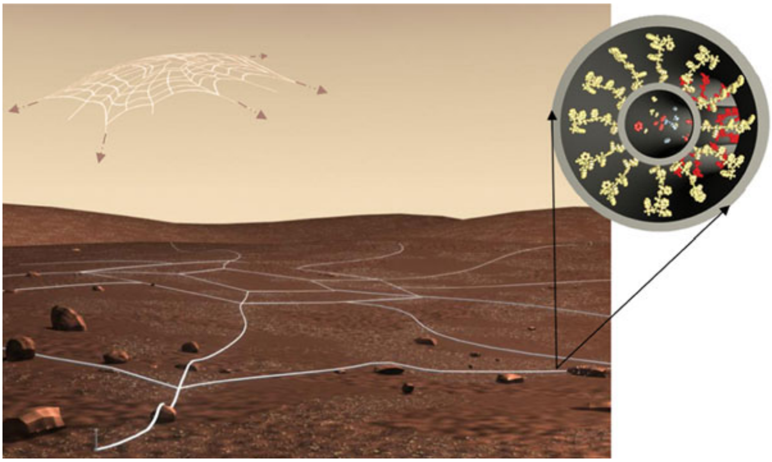


Fig. 1.12 A realistic scenario where the Networked TerraXplorers (NTXp) are employed. These meshes will be launched through the parachute and these will be spread open on the target surface. These NTXps could be launched in large quantities (hundreds) and hence the target terrain could be thoroughly mapped and sensed. A single NTXp could run into miles and when integrated with other NTXps could cover a vast terrain

1.3.2 Space Applications

Another application area where nanorobotics could be of great use is space. It is well known that the smaller a system launched in space is the smaller the mission cost is as well. In addition, for planetary exploration, due to the hazardous environment there is a need to deploy redundant systems for fault tolerance. The smaller and hence cheaper systems are much better for planetary deployment in large numbers. Nanotechnology and nanorobotics could provide solutions in the problem of miniaturization of space systems [88–90]. As an example of a possible future space application of nanorobotics we will present a concept developed by Dinos Mavroidis' group at Northeastern University during a NASA-funded project that targeted the development of revolutionary space systems [91].

Mapping and surveying a vast planetary terrain is a very difficult task. Some of the difficulties faced are limited area of landing for sophisticated planetary probes and rovers. It has been estimated that only a very small percentage of a planet's area is suited for landing. The planetary terrains and the atmospheric conditions pose a lot of difficulties for surface as well as air probes. Hence, only limited mobility could be achieved. Also, the investment required will be enormous for designing such rovers with capabilities of exploring the vast and difficult terrains.

Networked TerraXplorers is a concept shown in Fig. 1.12 in which various advantages of nanorobotic systems are being exploited such as their extremely light weight, low cost of manufacturing, mass scale production and bulk usage (billions), and their ability to self-assemble and self-organize. NTXp is a network of channels containing the nanorobots having enhanced sensing and signaling capabilities. This essentially is a static device, which could be easily projected onto a planetary surface, which is intended for exploration. The length of this device could be in miles, and yet it will be very light in weight. These could be easily packaged into small volumes appropriate for space missions. Also the power consumption for this device will be considerably less. The main consumption of power will be to maintain gradients for transporting the nanorobotic components inside these channels and for signaling and communicating with the main receiver.

The nanorobots will move inside the channels of the network and will have "limited" window of interaction through special valves with the outside environment. They will interact with the outside terrain and chemically sense the presence of water or other targeted resources/minerals. They will also act like a position sensor on the surface of the terrain enabling it with the capability to map the terrain geometrically. They will communicate with their main nodes and will pass the information about the terrain through them to the main receiver (which could be an altitude orbiter). These networks could be spread throughout the terrain irrespective of the topological constraints. Their mass production will be cheap as compared to any technology available now, which could be used to map a terrain. Furthermore, these networks could be used by future rovers or human explorers for tracing out the vast terrain and thereby guiding them to the direction they should follow. Discovery of caves and low-lying surfaces could be possible with the help of these networks. This information will be very crucial for future human explorations to any planetary terrains.

Chapter 5 discusses in more detail the use of nanorobotics in space applications.

1.3.3 Subterranean Exploration of Oil Reservoirs

The next application is an "unusual" one for nanorobotics: exploration of subterranean oil reservoirs and maximization of hydrocarbon recovery [92].

Although found in the subsurface, hydrocarbon is essentially located in a complex mix of water and in the pores of the "reservoir rock." A large amount of the removed oil is embedded in reservoir rock (most commonly limestone or sandstone) much like water in a sponge. The challenge is determining the reservoir rock's 3D geometry. Because of the reservoir rock's unpredictable shape and size, large amounts of oil are unaccounted because "pockets" are created rich with oil. Current technologies are restricted to analyzing the rock's properties within a 2 m radius around the drilled hole or from hundreds of meters above (at the surface) which tends to give vague results. Removing oil from the reservoir rocks is usually compared to "squeezing water out of a sponge." Due to the limitations in the current methods and technologies, large amounts of oil remain stranded in the already drilled wells. The August 2006 issues of the World Oil Magazine reported that an estimated 374 billion barrels (approximately 66 %) of the discovered oil remain stranded in the wells. Oil recovery can be substantially improved and facilitated if an accurate mapping of the oil reservoir “tubing” is known, i.e., getting 3D representation of the oil pathways (i.e., cracks in the rocks) in the reservoir. The network of cracks in the reservoir rocks and its properties is usually referred to as the “reservoir permeability field.” Therefore, detection, mapping, and predictive modeling of high permeability pathways in oil reservoir are of primary importance for efficient oil recovery.

Recently, nanotechnology has been proposed as a new technology field for assisting the oil industry in oil discovery, recovery, and processing. The Advanced Energy Consortium (AEC) was recently created by the Bureau of Economic Geology at the University of Texas in the Austin Jackson’s school of Geosciences (http://www.beg.utexas.edu/aec/index.htm) with the goal to improve energy production using micro and nanoscale technologies. The consortium includes members such as BP, Baker Hugnes, Conoco Phillips, Halliburton, Marathon, Occidental, and Schlumberger. Nanorobotics could be an important tool in this endeavor as it is shown by Saudi Aramco’s initiative on the development of nanoscale ***Resbots***, i.e., reservoir robots [92, 93]. More information on this subject can be found in Chap. 4.

1.4 NanoRobots: The Future

In this chapter we presented an overview of the nanorobotics field. This is a relatively new field where the robotics community started to be involved in a systematic way less than 15 years ago. Starting from large-scale manipulators that have nanoscale manipulation capability the robotics community quickly expanded into magnetically guided nanoparticles and protein, DNA, and bacterial-based nanorobotics. Definitely, we are still in a preliminary phase of the field and commercial applications have not been realized yet. However, it is clear that the future of nanorobotics is bright. We are at the dawn of a new era in which many disciplines are merging including robotics, mechanical, chemical and biomedical engineering, chemistry, biology, physics, and mathematics so that fully functional nanorobotic systems will be developed and used in important applications for humankind.

We foresee two major future research directions in this field. The first will focus on developing fully functional nanorobotic systems where all technological challenges due to the nanoscale environment will be resolved. The second research direction will focus more on applications where new nanorobotic products will be commercially available and new applications fields will be added.

There is no doubt that future technology development in nanorobotics will target to the development of fully functional and autonomous systems. Figure 1.13 shows a generic, futuristic, concept of a nanorobot in the form of a fish-like nanocapsule so that it can move in a fluidic environment. All the components needed for autonomous functionality of such a nanorobot are on-board. Most notably, propulsion, power generation, various types of sensing, wireless communication, and some computing power for limited intelligence have to be integrated into a small

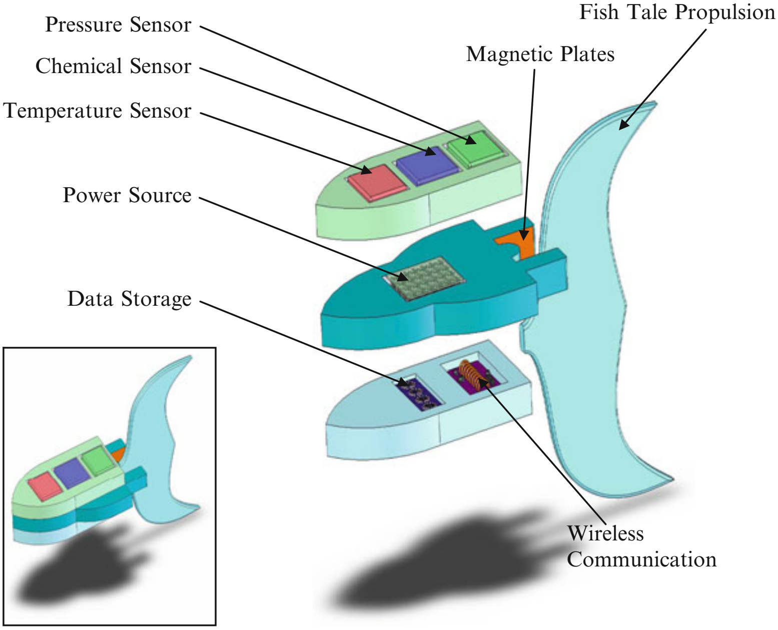


Fig. 1.13 Detailed view of a fully functional, autonomous nanorobot for in situ monitoring and its individual components

and strong structure so that the nanorobot could move in the fluidic environment using its own resources and be able to perform its task that in this case will be in situ monitoring.

Some of the components needed to materialize this concept exist today while others still need to be developed or improved before being used in a nanorobot. Manufacturing nanostructures, nanosensors of different types, and nanomotors are in an advanced development phase so we may consider that these components are one way or another available for integration in a nanorobot. However, onboard power generation, wireless communication, and computing capability have not been developed yet at a state where they could be used in a nanorobot even if some preliminary proof-of-concept prototypes for each one of these components have already been developed. Therefore, the robotics community in collaboration with the nanotechnology community should focus their near future efforts on improving the state of the art on onboard power, computing, and communication capabilities.

Furthermore, it is expected that the nanorobotics community will be actively working on new applications. Not only nanorobotic systems for the applications named earlier in this chapter (medical, space, oil industry) will be expanded and improved but new nanorobots for new applications will also emerge. Food industry, environmental monitoring and cleaning, military and counterterrorism systems, and industrial manufacturing are some of the applications areas where new nanorobotic systems are expected to be developed.

"There is plenty of room at the bottom" said Richard Feynman in his famous speech in 1959 at the California Institute of Technology raising for the first time the problem of manipulating and controlling objects at the nanoscale and setting this as one of the goals to achieve for future generations of scientists and engineers [94]. As a true prophet of the nanorobotics field he described in his talk for the first time ever his "small machines" being able to move in the blood vessel and perform surgeries. He raised numerous questions that relate to the manufacturing and operation of these "small machines" at the nanoscale. How can these "small machines" be manufactured? How can they be tele-operated in a "master–slave" configuration? How can power be generated for these small machines? "What would be the utility of such machines?" How do we perform assembly in a high viscosity nanoscale environment? All these very important questions raised over 50 years ago by an impressive pioneer of science are now ready to be answered by the current generation of nanoroboticists. But above all, as Richard Feynman suggested, let's "... have some fun" while we develop the next generation of nanorobotic systems!!

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