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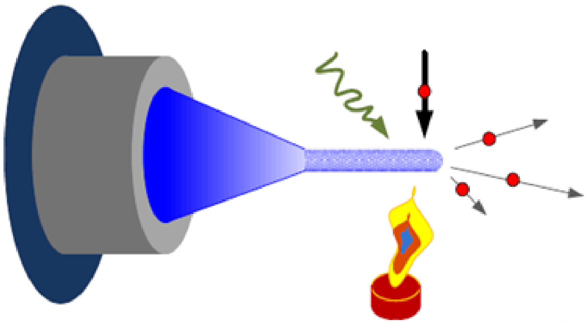

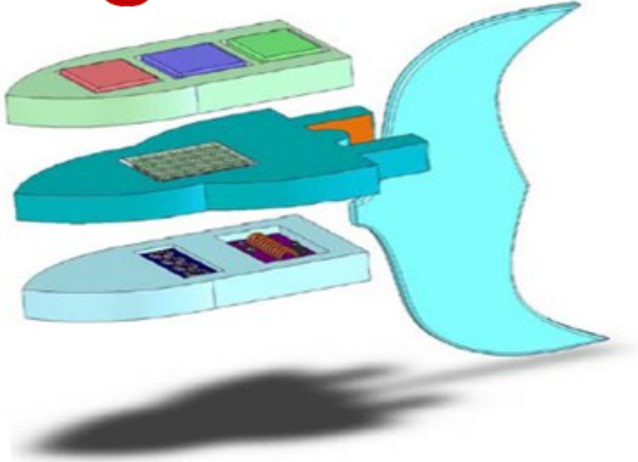

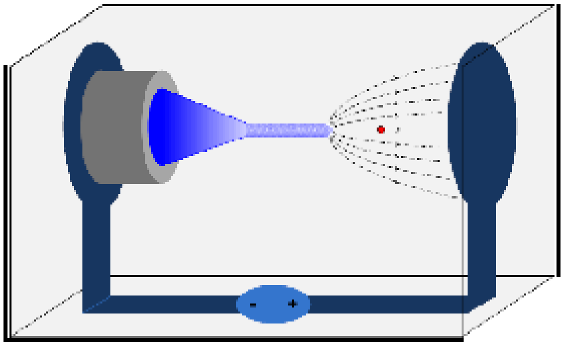

INSIDE THIS ISSUE:

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Editor`s Column

Welcome to the second issue of the NTC IEEE Nanotechnology Newsletter for 2011. Thank you very much for your readership and your invaluable comments on how to improve the newsletter. It is our hope that the newsletter will become a platform for both dissemination of information on the latest work on nanotechnology as well as for exchanging ideas. In this issue, I am happy to include two articles that report on the field emission properties of carbon nanotubes, and the applications of nano-robotics. Both Profs. Alireza and Low from the University of British Columbia and Nanyang Technical University respectively provide an overview of two exciting research areas in the field of nanotechnology. I encourage you to continue to support the newsletter by sending us commentaries, articles, news and whatever you think the general community of nanotechnology is interested in.

We look forward to hearing from you.

Sincerely,

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Electron emission from carbon nanotubes: field-emission and beyond

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The advantages of carbon nanotubes as potential electron emitters (sources) were recognized early on. Field-emission, that is the emission of electrons into vacuum through quantum mechanical tunneling as a result of the application of an external electric field, was already being investigated from nanotubes by the mid-1990s [1, 2]. Indeed, nanotubes have multiple attributes that make them almost ideal candidates for electron source applications. With a diameter of a few nanometers to a few tens of nanometers, and a length that can be macroscopic – centimetre long nanotubes are now grown routinely - a nanotube can have an extremely high aspect ratio. As such, under an external electric field, the local field at the nanotube tip can be enhanced significantly, making field-emission possible at relatively low applied voltages of a few volts per micrometer. High-aspect-ratio devices can also be made from bulk materials. However, not only achieving an aspect ratio and tip radius similar to that of a nanotube can be extremely difficult (if not practically impossible), but also a sharp tip carved out of a bulk material would suffer greatly from dangling bonds and loose atoms on the surface, potentially leading to significant instability and fluctuations in the emission properties, as well as short lifetime. A nanotube, being a chemically complete surface with high mechanical strength, would not suffer from the same issues. Nanotubes' ability to support extremely high current densities - up to 109 A/cm2 – is another advantage as the brightness of an electron source, a key parameter in the performance of electron-beam systems, is directly related to the amount of current emitted from the unit area of the source.

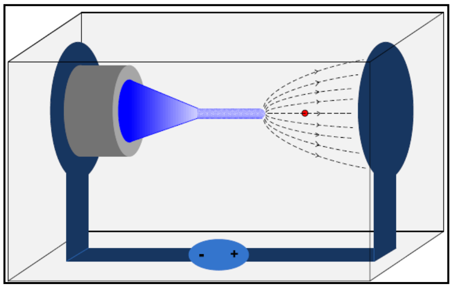

Figure 1: Schematic representation of a carbon nanotube field-emitter. The nanotube is mounted on a metal tip and acts as the cathode, emitting electrons that are collected by the anode on the right.

Perhaps even more intriguing than the above rather obvious properties of nanotubes that make them suitable as electron sources is the strong manifestation of quantum mechanical effects and rich variety of new physical phenomena that could potentially be exploited in controlling the electron emission properties. For example, the quasi-one-dimensionality of nanotubes and the sharp van Hove singularities in their density of states could lead to sources with narrow spread in the kinetic energy of the emitted electrons, a key factor in the performance of an electron-optical system.

The Fowler-Nordheim theory of field-emission [3- 6] has been used to analyze the behavior of nanotube field-emitters with considerable success [7, 8]. Nonetheless, the fact that a nanotube is not a planar emitter, and strong quantum confinement in the lateral dimensions as well as near the tip, add further complexity to the field-emission problem from nanotubes. More elaborate models are needed for a full treatment [9-11]. Indeed, deviation from Fowler-Nordheim behaviour [12, 13] and current saturation [8] have been observed. Although adsorbates seem to be one of the causes of this saturation behavior, saturation of current in pristine nanotubes has also been predicted [13]. Significant effort has been spent on the theoretical study of carbon nanotube field-emitters. Examples include investigation into the roles of apex diploes and field penetration [14], a theory of field- and thermionic emission from nanotubes, modifying the Fowler-Nordheim and Murphy-Good theories [15], usage of atomistic simulations in the prediction of nanotube field-emission properties [11, 16-20], calculation of the emission current using both continuum and atomistic approaches [13, 21, 22] and the investigation of the evolution of nanotube films and the emission current during field-emission [23].

With the advantages of nanotube electron sources also come the challenge of their characterization and usage. For example, determining the exact emission spot on a nanoscale electron source and investigating the emission pattern are important. Field-emission microscopy [24-26], transmission electron microscopy [27] and scanning electron microscopy [28] can reveal much in this regard. In one particular case, field-emission microscopy was used to monitor the growth of individual nanotubes, observing an axial rotation of the nanotubes during growth [29]. For applications such as the source in an electron microscope, an important challenge is to confine the emission to a small spot emitting precisely on the electron-optical axis. Another difficulty that hinders the usage of nanotubes for applications where individual nanotubes are needed is the lack of sufficient repeatability, given the variety of carbon nanotubes (in terms of chirality, diameter, tip structure and length) that are produced in a typical fabrication process. For more on nanotube field-emitters, review papers and books may be consulted [30-33].

Electron emission from nanotubes is not limited to field-emission. More recently, thermionic emission (emission of electrons by providing them with enough thermal energy to overcome the workfunction barrier) and photoemission (emission of electrons via the photoelectric effect) have been investigated. Although nanotubes are typically understood to be reasonably good thermal conductors [34 and the references therein] and, therefore, it might appear difficult to heat them to high enough temperatures, resistive heating of nanotubes has been reported. Cox *et al*. demonstrated thermionic emission from nanotubes, where they argued that the thermal conductivity of the nanotubes may be low due to defects, allowing effective heating [35]. Liu *et al.* reported thermionic emission from nanotube yarns [36]. Wei *et al.* showed thermionic emission from nanotube sheets and yarns connected between two electrodes [37]. It was observed that the nanotubes could be heated efficiently with negligible heat loss to the contacts. Thermionic emission could also be achieved through optical heating. Wong *et al.* used pulsed lasers at various wavelengths to excite electron emission from a film of nanotubes [38]. At wavelengths of 532 nm and 355 nm, corresponding to photon energies of 2.33 eV and 3.49, respectively, which are significantly below the workfunction of nanotubes (4-5 eV) [36, 39], thermally assisted field-emission took place. Note that laser-heated thermionic cathodes typically require high-power pulsed lasers. It was recently observed, however, that a forest of vertically aligned carbon nanotubes can be heated to more than 1,500 K using a continuous-wave laser at 532 nm and 488 nm wavelengths (2.33 eV and 2.54 eV photon energy, respectively) and emit electrons [40]. The key seems to be that, despite good electric contact between the nanotube`s bases and the substrate, which allowed the conduction of electrons, the thermal conductivity of the system was not very high, allowing the nanotube forest to be heated with relatively low powers of continuous-wave visible laser.

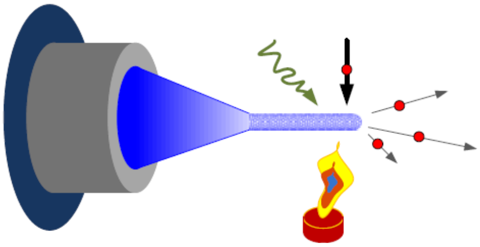

Figure 2: Electron emission from nanotubes can be induced by heating them or illuminating them with photons or other electrons.

The workfunction of nanotubes is in the range of 4-5 eV [36, 39]. Therefore, for photo-electron emission (or photoemission for short), ultra-violet photons with wavelengths in the 200-300 nm range are needed. Of course shorter wavelengths can be used to excite deeper valence or core level electrons. Indeed, much has been done on photo-electron spectroscopy of nanotubes using energetic ultra-violet or X-ray photons in order to study their electronic structure [41-48]. More recently, usage of lower-energy ultra-violet photons for photocathode applications has been investigated. Wong *et al.* reported field-assisted photoemission from films of nanotubes with a quantum efficiency of 2 x 10-7 using 266-nm photons from a pulsed laser [38]. We reported photoemission from a sparse collection of individual nanotubes using 266-nm photons from a continuous-wave laser [49]. The relatively large emission currents obtained pointed at efficient optical absorption in individual nanotubes, possibly due to optical antenna effects. Forests of millimetre long, vertically aligned carbon nanotubes have also been investigated for photocathode applications. A quantum efficiency of several orders of magnitude higher than that of random nanotube films was observed for photoemission from these forests using 266-nm light [50]. Photoemission with visible light is also possible if one finds a way to reduce the effective workfunction of nanotubes. For example, Westover *et* *al.* demonstrated the enhancement of thermionic emission from potassium-intercalated nanotubes by photoexcitation of electrons using a visible laser at 532 nm [51]. Another interesting development on light-controlled nanotube cathodes involves field-emitter arrays controlled by p-i-n photodiodes [52].

Photons are not the only type of particles used to induce electron emission from nanotubes. The interaction of “primary” electrons with nanotubes [53-56] and the resulting electron emission (secondary and backscattered electrons) have also been investigated [57-59]. This is an important topic from the point of view of imaging nanotubes, such as in electron microscopy [60- 64], as well as amplification of an electron beam through enhanced secondary electron emission or socalled stimulated field-emission from both collections of nanotubes and individual nanotubes, where electron gains of up to several thousand have been reported [65-67].

The use of nanotube electron sources has been demonstrated in a variety of applications. Luminescent tubes [68], flat-panel displays [69-72], x-ray generators [73- 75], electron microscopes [32, 76-78], mass spectrometers [79], free-electron lasers [80], parallel electron beam lithography and high-power microwave amplifiers [81] are only a few possible applications. Carbon nanotubes seem to have much to offer as electron sources. Despite the more than 15 years of research on nanotube electron emitters, these devices still have surprises for us, and much remains to be learned, both on the field-emission mechanism, and on more recently investigated effects such as thermionic and photo- and secondary electron emission. The author thanks the Natural Sciences and Engineering Research Council, the Canada Foundation for Innovation, The British Columbia Knowledge Development Fund, and the BCFRST Foundation/British Columbia Innovation Council for financial support of his work on carbon nanotube electron sources.

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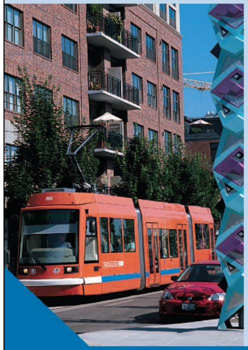

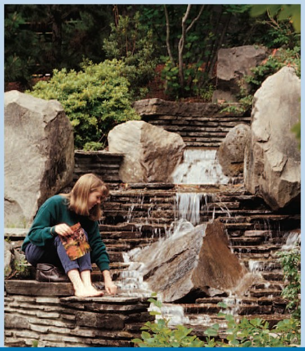

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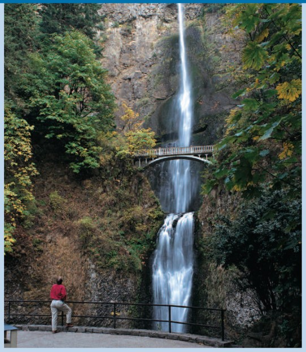

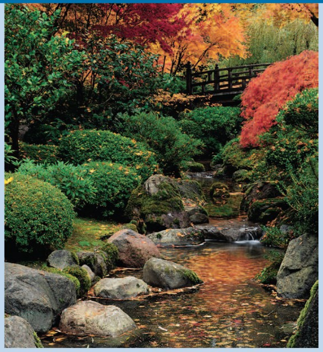

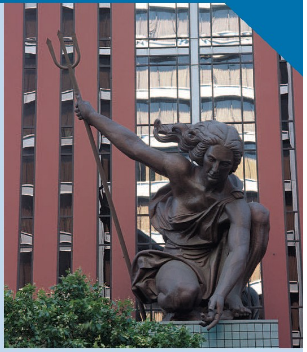

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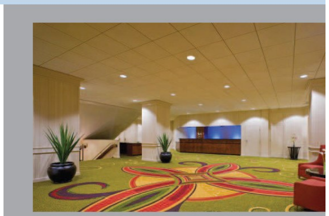

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Some Latest Developments in Nanorobotics

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Introduction

Miniaturised robots with millimetre and smaller dimensions (microrobots or nanorobots) have recently attracted great interest from the research community. In particular, nanorobotics is an emerging interdisciplinary technology area raising new scientific challenges and promising revolutionary advancements in applications, such as medicine, biology, manipulation, surveillance, environmental monitoring, and industrial manufacturing, used individually or in swarms. In definition, nanorobots are intelligent systems with overall dimensions at or below the micrometer range that are made of assemblies of nanoscale components with individual dimensions, ranging from one to one hundred nanometers. Nanorobots are expected to perform at least one of the following actions: actuation, sensing, signaling, information processing, intelligence, swarm behavior at the nano scale. Nanotechnology spans and merges disciplines dealing with matters in micro level (physics, chemistry, and biology) with those dealing with matters in macro level (engineering, materials science and computer science).

Several experimental devices, which can walk, climb vertical surfaces, fly, swim and even move within the human body, have been developed by researchers. With whatever the application, all manner of technical hurdles needs to be overcome before microrobots can become a commercial reality.

In an effort to disseminate the current advances in nanorobotics, this newsletter describes some works and the growing interest of the robotics community, particularly in the area of healthcare and surveillance.

Applications of Nanorobotics

Applications in Medical Fields

A growing body of research has developed miniature medical robots, which can enter and move freely within the body. Bogue [1] provides an excellent introduction to this technology and a review of recent progress. Medical microrobots can be thought of as miniaturised, self-powered, mobile devices with characteristic dimensions in the sub-mm region and aimed at in vivo applications. It is hoped that the device could travel through blood vessels, the spinal canal, the urethra, or even the alimentary system to undertake a range of clinical tasks.

Other important fields include biology (manipulation, sorting, combining cells, etc.) and medical technology. In surgery, the use of steerable catheters and endoscopes is very attractive and the development of increasingly small microrobotic devices has been actively progressing [1]. Wireless untethered microrobots that will explore, repair, or “cure” our bodies (“swallowing the surgeon”) appear to be achievable goals in future. In fact, endoscopy using wireless capsules (camera pills) are already available in the market and allow for endoscopic imaging of the entire gastrointestinal tract, something currently not possible using standard scopes. Steering or crawling motion by magnetic way is suggested for such devices to locomote in a controlled fashion. In this way, doctors could steer pill-mounted cameras and other actuators to the areas of interest for visual investigation and biopsies beyond the range of current endoscopes.

Funded by the European Commission’s Sixth Framework Programme [1], a research project involving eighteen organizations from nine European countries aiming to exploit the latest developments in MEMS and nanotechnology to fabricate a miniaturised robotic “pill” for advanced cancer diagnostics and therapy in the human digestive tract (see Figure 1). It is hope that the nano device will take the form of an actively controllable, miniature capsule endoscope, equipped with a vision system and operating instruments. It is hoped that the nano device not only detects stomach and bowel cancer in the early stages but also treat it, in situ. This is possible by equipping the capsules with miniaturised grippers to remove and/or destroy diseased tissues.

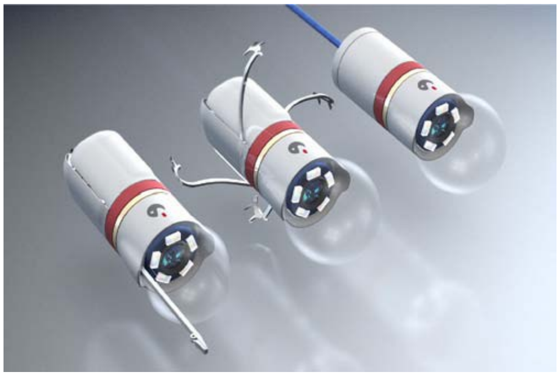

Figure 1. Images of variants of the VECTOR endoscopic robots, operating within a human bowel (*source*: http://www.vector-project.com/index.html)

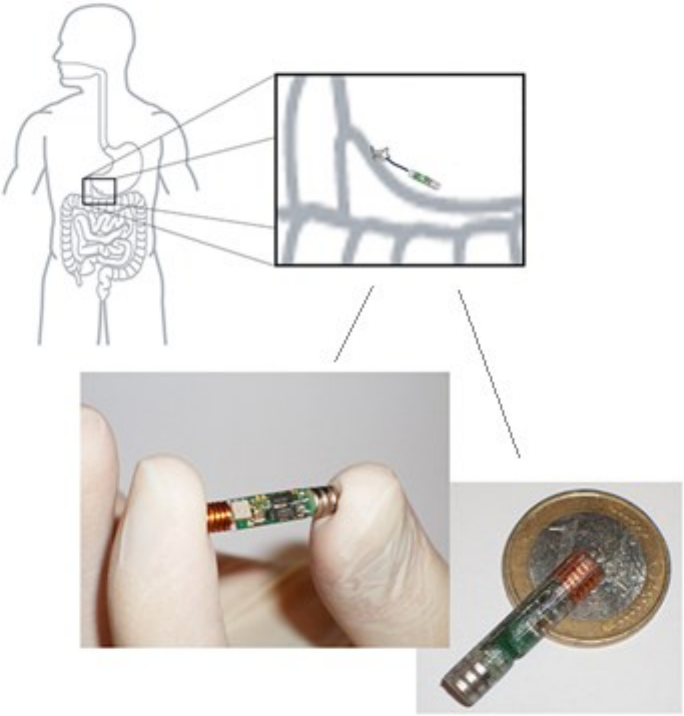

Figure 2. Device of bleeding detection implant
(*source*: http://www.vector-project.com/project/results_wp15.html)

Medical nanorobots can be taken as microscopic devices measured in the scale of nanometers. As these medical nanorobots are able to move inside the human body, identify the particular harmful cells (and try to quarantine it or may destroy the harmful cell itself), they can be used to cure many diseases with negligible harm to the body.

To perform these tasks inside the body, the nanorobots might receive the energy from the body itself. (In the form of *heat* produced inside the body or *glucose* or *sugars* which are present in the body itself). It is expected that [1]someone diagnosed with cancer might be offered a new alternative to chemotherapy in future. Note that the traditional treatment of radiation that kills not just cancer cells, but healthy human cells as well, causing hair loss, fatigue, nausea, depression, and/or other undesired symptoms.

Advanced nanorobots will be able to sense and adapt to environmental stimuli, such as heat, light, sounds, surface textures, and chemicals; perform complex calculations; move, communicate, and work together; conduct molecular assembly; and, to some extent, *repair or even replicate themselves*.

Applications of nanorobots are expected to provide remarkable possibilities. An interesting utilization of nanorobots may be their attachment to transmigrating inflammatory cells or white blood cells, to reach inflamed tissues, and assist in their healing process [2]. Nanorobots can also be applied in chemotherapy to combat cancer through precise chemical dosage administration [3]; and nanorobots might be used to locate and break kidney stones.

Several researchers have been working on the navigation of navigate micro-mechanisms through human blood vessels. Nevertheless, these microrobots are difficult to be fully controlled [4]. Examples of partially autonomous systems are the concept for so called smart pills equipped with video cameras. In the beginning of the process, the pill is swallowed and transported to the part of the body to measure or record a video sequence. The information of the measured parameter or the signals from the camera is then transmitted out of the body. The position of the pill inside the body can be located by X-ray or ultrasound. As soon as the pill reaches an infected area, a drug encapsulated in the pill can be released by the actuators onboard. External communication could be realized through radio signals or other means.

Applications for Surveillance

This section will present the application of nano-technology to surveillance by using hair-cell sensors. The lateral line is a hydro dynamic imaging system found in fish (see Figure 3) [5]. It enables fish to accomplish a variety of underwater activities, such as localization of moving prey/predators [6, 7], detection of stationary objects [8], schooling [9], rheotaxis [10], and social communication [11].

A lateral line consists of numerous hair cell sensors, which is so called neuromasts. They are distributed all over the fish body, with many of them situated on the surface of the skin and others in sub epidermal canals (see Figure 3) [12, 13]. Each neuromast has ciliary bundles encapsulated in a gelatinous cap, which is known as acupula. The cupula provides a mechanical linkage between the neuromast and the external hydrodynamic environment. The drag force acting on the neuromast causes the cupula of the neuromast to bend or slide [14, 15]. The movement of the cupula further leads to the deflection of the ciliary bundles inside the cupula and elicits neuron-spiking activities of the underlying hair cells [16]. By the arrangement of neuromast array along the body functioning as the lateral- line system, the fish is able to encode spatial excitation patterns of a hydro dynamic stimulus [17-19]. It has been shown that the lateral line allows fish to navigate in the absence of vision and chemosense [20, 21].

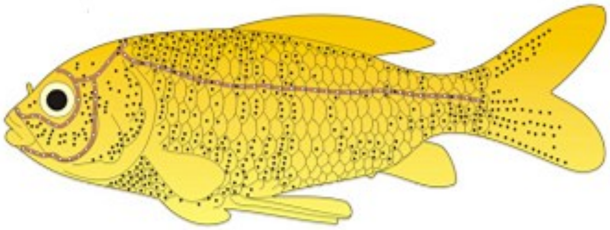

Figure 3. The lateral line and the neuromasts of fish [13]. Black dots indicate position of neuromasts on the skin surface, while white dots on the thick brown line show the approximate positions of neuromasts in sub epidermal lateral line canals.

A man-made lateral line system can be indispensable for underwater robotic vehicles, which enabling new ways of exploration, interaction and communication. The above-mentioned lateral line sense can supplement the current underwater sensing methods, including sonar and vision. It can also be used together with servomotor or micromotor to form a hybrid system in micro-UAV or micro-AUV [2]. Nanosensors can be placed at various locations, as illustrated in Figure 4. In the long term, the bio-inspired sensing technique will provide a reserach platform that can be used to test biological hypotheses.

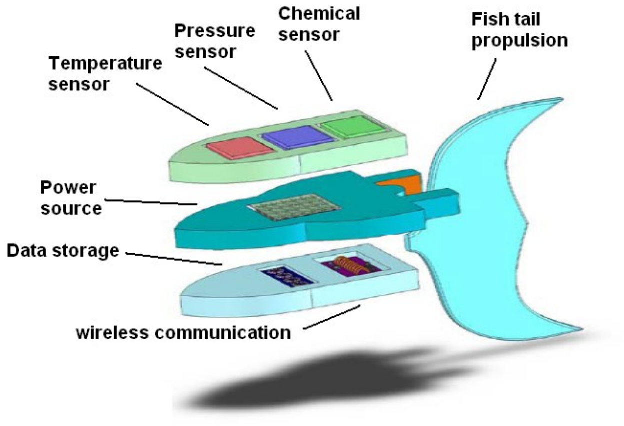

Figure 4. Assembly of a Fully Functional Nanorobot (source: *Nanorobotics in Medical Applications: From Science Fiction to Reality* by Constantinos Mavroidis)

Future Challenges of Bio-nanorobotics

Scaling issues

As we downscale robots to sub millimeter dimensions, the relative importance of physical effects changed [4]. As the size of device is reduced, surface effects and fluid viscosity dominate over inertia and other volumetric effects, and power storage becomes a key issue. Furthermore, microrobots, like microorganisms, swim in a low-Reynolds-number regime, requiring swimming methods that differ from macroscale swimmers [22]. This places significant constraints on the development of medical microrobots.

In traditional robotics, it is often easy to compartmentalize aspects of robot design such as kinematics, power, and control. However, in the design of wireless microrobots, fabrication is fundamentally limited by scaling issues. Power and control are often inextricably linked to these issues. Engineers would need to give up intuition gained from observing and designing in the macroscale physical world, and instead rely on analysis and simulation to explore microrobot design [23].

Actuator issues

Electrostatics, electromagnetic and piezoelectrics are the most common ways to realize actuation at micro scales. For micro-robotic manipulation, besides micro resolution and compact sizes, actuators generating large strokes and high forces are best suited for such applications. During the design of an actuator, trade-offs among several factors must be taken into consideration. The factors include range of motion, force, speed (actuation frequency), power consumption, control accuracy, system reliability, robustness, load capacity, etc.

Power and Propulsion: magnetic approach

One of the critical technological challenges in nanorobotics design is powering the propulsion system. Owing to difficulties in storing energy at these scales, techniques are required to remotely “powering” the devices or harvesting energy from the environment.

Many research groups investigate magnetically-powered microrobots [24]. For example, a UW research group (see http://newsrelease.uwaterloo.ca/news.php?id=5055) has developed the world's first flying microrobot capable of manipulating objects for microscale applications. On the other hand, an ETH group [25] reported a micro miniaturised device, which is similar in size and shape to a flagellum – the miniature tail on certain bacteria that is used to propel them. The device measures 25-60mm in length and is fabricated from layers of indium, gallium, arsenic and chromium, with its “head” made of chrome, nickel and gold.

Another magnetic propulsion concept involves the use of magnetotactic bacteria, which respond to external magnetic fields. A group from the Canadian Ecole Polytechnique in Montreal [26] has pioneered the use of the bacteria themselves, as the means of propulsion in experimental microrobots and other devices. These can be magnetically monitored, steered and located and travel through liquids at speeds of up to 200mm/s.

Concluding Remarks

While the devices discussed so far are microrobots, although some are described as nanorobots, the development of future nanorobots is rapidly gaining pace [27-29]. These would have submicron dimensions and applications are anticipated in healthcare and bioengineering, together with the applications in nanomanufacturing and other automated nanoscale operations. As yet, the technology is in its infancy but a growing number of academic groups are actively involved in studying nanorobotic concepts and implementation.

The development of medical microrobots poses an enormous, multi-disciplinary challenge. It involves a wide and diverse range of technologies and disciplines, such as silicon microtechnology and MEMS, nanotechnology and NEMS, micro-electronics, bioengineering, materials science, electromagnetism and hydrodynamics. Consequently, successful research projects are likely to necessitate collaboration between groups with differing, but complementary fields of expertise.

Acknowledgements

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Su	M	Tu	W	Th	Fri	Sa
					1	2
3	4	5	6	7	8	9
10	11	12	13	14	15	16
17	18	19	20	21	22	23
24	25	26	27	28	29	30
31						

August 2011

Su	M	Tu	W	Th	Fri	Sa
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30	31			

September 2011

Su	M	Tu	W	Th	Fri	Sa
				1	2	3
4	5	6	7	8	9	10
11	12	13	14	15	16	17
18	19	20	21	22	23	24
25	26	27	28	29	30	