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A Review of Selected Nanotechnology Topics and Their Potential Military Applications

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ABSTRACT

This report presents the review of progress in selected nanotechology topics and some possible applications. We survey four major branches within the field: nanotubes, quantum dots, nanomaterials and nanodevices. For each of these, we review the underlying scientific concepts, potential enabling technologies and current limitations to the realisation of nanotechnology applications. Possible implications for the future Land Force are discussed by examining potential nanotechnology impacts across seven core military skills within the Army-as-a-System construct.

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Executive Summary

Nanotechnology is one of the most significant research areas to emerge in the past decade or so. It is based on the concept of creating applications based on components built at the very small (nano-) scale. While only a relatively new field, the impact of nanotechnology is already being felt. Indeed, many believe that as nanotechnology matures as a technology and an increasing number of applications become commercially viable, it will fundamentally alter how societies function. The field draws on knowledge and expertise from many (if not all) science and engineering disciplines, integrating aspects of physics, chemistry, biology, material sciences, and biological and chemical engineering. Applications span the spectrum stretching from mature products such as new sunscreens, through emerging ones such as bio- or chemical sensors, to imaginative and yet-to-be conceived products (such as self-replicating microscopic robot systems) which are currently in the realms of scientific fiction.

This study explores the field of nanotechnology and discusses its possible impacts with a specific focus on military capability. It forms part of an ongoing study of the potential impacts of enabling technology on concepts for the Army After Next (AAN). In this report, we survey the potential applications of some topics in nanotechnology. Decomposing the nanotechnology topics into four major themes: nanotubes; quantum dots; nanomaterials; and nanodevices, we review, for each branch, the underlying science, postulate possible enabling technologies, suggest end-user products, and highlight current limitations and key indicators to be met for commercialisation.

We then discuss the potential impact of nanotechnology on the development of the AAN by examining possible influences of nanotechnology on the seven core Land Force skills defined within the 'Army-as-a-System' construct, namely: engagement, movement, protection, decision making, communication, sustainment, and information collection. We indicate characteristics of nanotechnologies, such as reduced weight and size, and increased strength, that provide a number of opportunities for the enhancement of military capabilities. Although not comprehensive, this allows an appreciation of nanotechnology-driven technology concepts and their potential effects. In doing so, it highlights the broader implications of this technology discipline and so provides a basis to inform the development of new warfighting concepts in the AAN timeframe.

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Contents

Glossary

AAAS	Army-as-a-System
AAN	Army After Next
AFM	Atomic Force Microscopy
ET	Enabling Technology
GMR	Giant Magnetoresistance
LED	Light-emitting Diodes
MEMS	Microelectromechanical systems
MWNT	Multi-wall Nanotubes
NEMS	Nanoelectromechanical systems
QD	Quantum Dots
SPM	Scanning Probe Microscopes
STM	Scanning Tunnelling Microscopes
SWNT	Single–wall Nanotubes
TBV	Technology Based Variables

1. Introduction

Nanotechnology is one of the most significant research areas to emerge in the past decade or so. It is based on the concept of creating applications based on components built at the very small (nano-) scale. While only a relatively new field, the impact of nanotechnology is already being felt. Indeed, many believe that as nanotechnology matures as a technology and an increasing number of applications become commercially viable, it will fundamentally alter how societies function. The field draws on knowledge and expertise from many (if not all) science and engineering disciplines, integrating aspects of physics, chemistry, biology, material sciences, and biological and chemical engineering. Applications span the spectrum stretching from mature products such as new sunscreens, through emerging ones such as bio- or chemical sensors, to imaginative and yet-to-be conceived products (such as self-replicating microscopic robot systems) that are currently in the realms of scientific fiction. Given the range of potential military applications [1-3], the increasing level of R&D, increasing demand and the potential depth of market penetration [4], it is becoming one of the key technology areas. As such, it is almost certain to have a remarkable impact on military capabilities in the next 15-30 year timeframe [2, 3, 5]. Therefore, a considered deliberation on how nanotechnology will impact is essential.

This report, which forms a part of a series of studies of the impact of Enabling Technology (ET) on Army After Next (AAN) [5-8], introduces some of the potential applications of nanotechnology. As our focus is on the potential implications and applications to the military arena, we do not go into the detailed technical aspects of this field. As this is a rapidly evolving field, we include both the mature and emerging applications of nanotechnology, which are expected in the market in a short or medium term timeframe, along with those at the fundamental scientific research level (such as nanoelectronics) and visionary ones that have yet to make it beyond the conceptual stage (such as nanobots). However, as most potential applications of nanotechnology are still under development, there is some uncertainty as to when and if some particular application will be realised. As such, this report includes both assessments on the potential of nanotechnology and obstacles that need to be overcome for such applications to be delivered, and therefore key indicators that need to be met for the realisation of these ETs.

Of course, we wish to understand the potential impacts that nanotechnology-based technology concepts may have on future warfighting. So we conclude this report by examining their potential applicability within the military context and the possible impact of nanotechnology on land warfare. To do this we discuss potential application areas, by employing the 'Army-as-a-System' (AAAS) framework [9-11] to postulate how nanotechnology might deliver novel effects within the future battlespace. We note, of course, that with the ongoing emergence of nanotechnology, in terms of development and application, this report is a work in progress and is open for comment and continual review.

In the next section we give a very brief background to nanotechnology, following this with a brief survey of some key nanotechnology areas. Sections 3 and 4 focus on particular domains of nanotechnology, namely nanomaterials and nanodevices. We consider potential applications in section 5 and conclude with a discussion of the possible implications of nanotechnology on the future Land Force in section 6.

2. Overview of Nanotechnology

2.1 Background

Nanotechnology is relatively new, continually evolving and developing from a range of scientific disciplines. So, not surprisingly, there are a variety of opinions on what constitutes nanotechnology. Some describe nanotechnology as "a vision, a hope to manufacture on the length scale of a few atoms" [12], while others believe that "nanotechnology – in the guise of nanoscale materials – has already been around for a long time" [12] through such processes as the addition of nano-sized carbon particles to reinforce tyres. There is also an apparent disparity of opinion as to the meaning of the term 'nanotechnology'. Some believe that nanotechnology is largely a field of science and not a technology since it involves fundamental research on the structure of matter [13] (in that sense, 'nanoscience' is perhaps a more appropriate name for this field). One of the definitions provided is "nanotechnology is the principle of atom manipulation atom by atom, through control of the structure of matter at the molecular level" [14]. We believe that this definition is too narrow because it limits nanotechnology as a discipline to building materials atom by atom, i.e. bottom-up, while we know that the other route being actively pursued by researchers is the miniaturization of existing technology, i.e. top-down. As such, in this work, nanotechnology refers to "any application of science dealing with elements between 100 nanometer and 0.1 nanometer where size is critical to performance" [15][1]. The US National Science Foundation has adopted a similar definition [13].

Given the wide range of potential applications, nanotechnology has become one of the growth areas in research and development in recent years. According to a recent report [16], the budget of the US National Nanotechnology Initiative for financial year 2002 was \$604 million, increasing by 20% to \$710.2 million[2] for 2003. Indeed, between 1997 and 2001, total US funding for nanotechnology increased from less than \$500 million to more than \$1250 million [13]. Europe is also investing significant resources into nanotechnology research, \$180 million in 2002, increasing to between \$270 million and \$315 million in 2003 (up at least 50%). Importantly, nanotechnology has become a key focus area for the US military with their Department of Defense building a new nanotechnology research centre (The Institute for Soldier Nanotechnologies) in 2002 with scheduled funding of \$50 million

[1] One nanometre (nm) = one billionth (10^{-9}) of a metre.

[2] All amounts quoted are in US \$.

for the initial five years [3]. Such significant growth in research funding and the establishment of dedicated military research programs for nanotechnology indicate that the future Land Force capabilities may be fundamentally different from that of today.

2.2 Survey of some major nanotechnology domains

Given the variety of views in terms of development and application, we cannot expect to provide a comprehensive tome on nanotechnology. There are a number of reports discussing the potential impact of nanotechnology development and associated implications [17, 18]. Instead, we undertake a survey of the areas of application and potential implications for the military. We conducted an environmental scan on the area, capturing data from various sources such as research reports, feature articles, and scientific news, across many different journals. We have attempted and are attempting to continually update data on nanotechnology by constantly monitoring publications for new developments and applications. Of course, we have only limited control over the quality of the data sourced and have, where possible, attempted to overcome any errors or biases due to such sources by supplementing information with published and unpublished information.

The first step in this process is to gain some understanding of where nanotechnology development and applications may be heading. A report produced by venture-capital company '3i', in association with the UK's Institute of Nanotechnology and the Economist Intelligence Unit discussed the prospects for commercial applications of nanotechnology, based on a survey of almost 100 nanotechnology experts worldwide [15, 19]. The survey[3] indicated that the most promising potential applications of nanotechnology products for the next five years are smart paints, pigments and coating, while the 'hottest' areas for 10-15 year timeframe were in personal-health diagnostics [19]. Other surveys of experts suggest that it will have its greatest impact in the information technology arena (especially in information services) [20], or on its potential mechanical capacity (such as miniature autonomous machines) [2].

Our environmental scan suggested that nanotechnology can be divided into two discrete classes depending on whether the focus is on scientific research and development of particular nano-properties that make up the building blocks for applications (nanomaterials) or on the invention of functional systems (nanodevices)[4].

Within the domain of nanomaterials, we have focussed on three particular areas:

- Nanotubes, macro-molecules with novel or exceptional properties (many of which are continually being discovered) and whose application spectrum currently extends from commercialised 'new types of lamps' to highly speculative 'crash-proof vehicles';

[3] We are cognisant that the aim of the survey was to provide investment advice on start-up nanotechnology companies and therefore the focus was for the delivery of products in the short to medium timeframe.

[4] We note that the classification and class names introduced here are only for assistance in structuring this report.

- Quantum dots (QD), in effect tuneable small semiconductor crystals which can be designed to produce specific fundamental properties; and
- Nanostructured materials, 'normal' materials, such as metals, ceramics, alloys, that exhibiting novel collective properties.

While the above three are at the different scales of physical structures (nano, micro and macroscopic), we grouped them into the same class because they all need to be integrated with other components into a system to do something useful. Each is discussed (where relevant) in terms of chemical, electronic, optical, and mechanical properties, followed by a discussion of some remaining technical obstacles for each.

In conjunction with the ongoing discovery of new properties and new applications of nanomaterials, significant effort is being focussed on research into and development of nanodevices. By and large, these comprise electromechanical systems scaled down to the nano-level (i.e. miniature machines performing tasks that are currently possible, only on a smaller scale). However nanotechnology developments may also lead to novel applications, especially for activities that are scale specific. Certainly many have been noted, and range from being quite mature to very speculative. As we cannot do justice to all of these, we have selected two particular areas that have, in our opinion, significant potential from the military perspective. These are:

- Miniature electromechanical systems, similar to our daily machines in structure comprising integrated mechanical and electronic components, which can be divided into:
    - Microelectromechanical systems[5] (MEMS) – small-scale (at the micron level)
    - Nanoelectromechanical systems (NEMS) – similar to MEMS, but at the nanoscale
- Nanobots – programmable, potentially self-replicating, molecular machines made of specifically arranged atoms.

Again, we note that the main distinguishing feature is scale (molecular, nano or micro).

3. Nanomaterials

3.1 Nanotubes

3.1.1 Introduction

Nanotubes are tubular molecules formed by folding sheets of atoms. There are two types of nanotubes, classified by the number of walls forming them. Single-wall nanotubes (SWNT) are formed by rolling up a sheet of graphene [21]. Graphene is a two-dimensional graphite lattice structure consisting of a network of hexagonal rings of carbon atoms (i.e.

[5] While MEMS are not formally classified as nanotechnology, they have been included as their relative maturity provides some insight into possible future NEMS applications. In addition, MEMS provide a likely intermediate point in integration of nanotechnology into military capability.

like a sheet of chicken wire) [22]. Multi-wall nanotubes (MWNT) consist of a number of concentric graphene tubes [22]. The typical diameter of a SWNT is approximately 1 or 2 nm [23] whereas a MWNT can be tens of nanometres across [24]. MWNT are easier and less expensive to produce but have a higher occurrence of structural defects. Gram for gram, a SWNT is 70 times as expensive as gold [25]. Hence, balancing the utility of the SWNT and the availability of the MWNT is at the heart of current issues in the engineering of nanotubes.

While research on carbon nanotubes dominates, there are reports on successful synthesis of non-carbon nanotubes, such as boron nitride nanotubes [26, 27]. However, the technology importance of these non-carbon nanotubes is far from clear, and hence only carbon nanotubes are considered in this report.

Nanotubes have a wide range of applications, with products including super-strong personal protection, efficient illumination and display equipments, hypersensitive chemical sensors, to name just a few. Indeed, the US company, Hyperion, has launched more than three dozen nanotube products that are used in a diverse range of applications such as automobiles, computer hard drives, and packaging, and have stated that "Literally *anything* can be improved upon with use of nanotubes. Our customers are actively working to improve upon or find new uses for nanotubes" [28]. Therefore, it is unrealistic to review nanotube applications exhaustively because the topic is too large and changing too rapidly. As such, our selection of nanotube applications focuses on those that are most likely to have significant military utility.

3.1.2 Nanotube properties

3.1.2.1 Mechanical

The ability of nanotubes to improve the strength of materials is based on their remarkable mechanical properties. Each carbon atom in a nanotube is bonded to three neighbouring atoms, allowing the formation of one of the strongest bonds found in nature [29]. Often referred to as the "ultimate fibre" [22], they rank among the strongest materials known [29]. In particular, nanotubes can be:

- about 20 and 100 times stronger than high-strength alloys [23] and steel [30], respectively;
- exceptionally resilient (restraightened without damage after bending at large angles) [23];
- ultra-light weight at many times less the effective weight of steel [30]; and
- five times stiffer than steel (by the measured value of Young's modulus) [21].

3.1.2.2 Electronic

Nanotubes also display unique electronic properties. Depending on how the graphene sheets are rolled up to form a cylinder [29], a nanotube can display the properties of either metals (conductors) or of semiconductors, producing a 'metallic' nanotube if rolled along its length or a semiconducting one when by rolled askew [25]. This peculiarity is derived from the specific electronic band structure of graphene and has led to graphene being described as a "semi-metal" [21].

3.1.3 Nanotube applications

3.1.3.1 Mechanical applications

The outstanding mechanical properties of nanotubes have already been identified as lending themselves to a number of militarily useful technology concepts such as:

- Ultra-strong, lightweight body armour [24, 31];
- Artificial muscles for robots and possibly for exoskeletons [32, 33];
- Crash-proof vehicles [24]; and
- Long-lasting lithium-ion batteries used in cell phones and notebook computers (already on the market) [34].

It is interesting to note that while the mechanical properties of nanotubes are remarkable, their use to reinforce macroscopic materials (fabrics, alloys, metals) is currently quite speculative for reasons discussed in the later sections. However, some experts suggest that materials made from nanotube threads, such as bullet-proof vests weighing no more than the average shirt, could be available in the next few years [31, 35]. For example, there has been some suggestion that spider silk-like fabrics can replace the current body-armour materials [36].

3.1.3.2 Electronic applications

While the applications of nanotubes in creating super-strong, lightweight and highly flexible materials are still conjectural, electronic applications are appearing with some products already on the market. Certainly, nanotubes have excellent conduction and transmission properties [24], which lend themselves to electronic applications. Four such applications are:

- **Illumination and display:** The process for an electronic device emitting electrons under an applied voltage or electrical field is called field emission, which is important for illumination and display purposes. Nanotubes are capable of emitting high density electron beams under a relatively low voltage and are therefore excellent field emitters [24]. Based on this electronic behaviour, companies have started developing nanotube-field-emitter products such as:
    - o Efficient, durable lamps (twice as bright as conventional light-bulbs, longer-life and at least 10 times more energy-efficient) [23]; and
    - o More power-efficient and thinner monitors (as bright as cathode-ray tubes but consuming only 10% as much power) [23]. Samsung of Japan is expected to put its nanotube-based full-colour display on the market by December 2003 [34]. A flat screen display based on nanotubes, developed by CSIRO, is expected on the market in 2004 [17].
- **Nanotube-based circuitry:** It is expected that nanotubes will play an important role in future nanoelectronics, as nanotubes can be used as interconnecting wires between

electronic components in microchips at a very small scale[6]. In order to incorporate more components in microchips, thinner wires are needed. However, two problems arise from scaling down the size of metal wires: overheating and reduced reliability. These problems could be solved by using nanotubes as interconnecting wires because they are excellent thermal conductors and can transport high-density beams of electrons without being damaged [23]. Nanotubes have been used to build nano-scale diodes and transistors [23] and have been assembled into basic logic circuits [37].

- **Conducting plastics**: While plastics are familiar in daily life for their use in insulation around wires and electrical equipments, some types of plastics can be made into semiconductors or conductors of electricity [38]. With added nanotubes, conducting plastics, such as polyaniline, can conduct better than copper [25]. Weight savings (and therefore low fuel consumption) can be gained by replacing heavy copper wires in aircrafts with nanotube-improved plastic wires [25]. Nanotube-enhanced conductive plastics can be used for electrostatic dissipation in electronic devices and electromagnetic-wave shielding [31, 34] to protect battlefield communication systems from interference. In addition, they can improve the efficiency of plastic solar cells by a factor of up to 50,000 [25], as nanotube-formed networks provide a path for electrons to reach electrodes in these plastic solar cells. So while nanotube-improved plastic solar cells are many times less efficient than the best silicon solar cells (5% in conversion of light into electricity in contrast with 15% efficiency of silicon cells), they are cheap, and are open to further improvements in efficiency [25].
- **Nanotube-enhanced piezoelectric plastics:** Piezoelectric materials are a class of 'smart materials' that produce a voltage (therefore power) when they expand and/or contract [39]. With the addition of nanotubes, one type of piezoelectric plastics was found to be three times as sensitive to pressure [25]. One potential application is to create electricity by weaving these nanotube-enhanced piezoelectric into plastic sails [25].

3.1.3.3 Hydrogen storage for fuel cells

Another potential application for nanotubes is in the use of fuel cells. These are devices that generate power by combining hydrogen and oxygen, thus providing the opportunity to replace hydrocarbon-based engines. Fuel cells have been investigated as one alternative to the internal combustion engine of vehicles [40], as they have the potential to create automobiles that are quiet, efficient and clean [41].

One potential drawback of fuel cells is that they derive their energy from hydrogen. Hydrogen gas is hard to store as it is inflammable, potentially explosive and needs high-pressure tanks for storage, making it uneconomical and potentially unsafe. The alternative, liquefied hydrogen is not practical, as it requires low temperatures to remain liquid. Therefore, a technical challenge for the practical fuel-cell vehicle is the development of an effective, safe, compact and economical hydrogen-storage technology [34].

Under the right external conditions, such as pressure and temperature, nanotubes can enclose hydrogen atoms inside their cylindrical pores or into the channels between the

[6] Metal wires about 250 nm in diameter are currently used in such circuits.

tubes [42]. By changing the ambient conditions, the captured hydrogen could be released to feed the fuel cell and generate power. The technical target, set by the US Department of Energy, is 6.5 wt% (i.e. 6.5% of total weight attributable to the hydrogen) [42]. However, the feasibility of using nanotubes to store hydrogen remains unclear. As of 1999, 4 wt% was the best 'confirmed' result, as some claims exceeding 6.5 wt% have proved difficult to reproduce [43]. While a result of 7 wt% at room temperature was reported recently, another group repeating the same experiments obtained only 1.5 wt% [42, 44]. Some of this confusion relates to commercial sponsorship, as securing intellectual property rights before publishing full details of research works is the commercial norm [42, 44].

3.1.3.4 Nanotube tools

Nanotubes themselves can be used as an enabler for the development of other nanotechnologies by creating tools that can be applied to manufacturing at the nano-scale. Applications such as scanning microscopy, nanolithography and nanotweezers have been identified as some of the most promising endeavours as they can enhance capability of atomic manipulation in scientific research and development.

- **Scanning microscope**: Nanotubes can be used as the stylus tips in scanning probe microscopes (SPM), which are important tools to observe structure on the nano-scale. These nanotube-tips are commercially available (e.g., Seiko Instruments, Japan) [34] and are not only more durable due to their strength, but they may also boost the lateral resolution of a SPM by a factor of 10, allowing a clearer view of proteins and molecules [23]. Nanotube-tips can also be employed to investigate deep crevices that are otherwise inaccessible using conventional tips [23, 29].
- **Nanolithography:** Used as SPM probes, nanotubes can facilitate nanofabrication using methods such as dip-pen lithography [13, 45]. In this case, Atomic Force Microscopes (AFM) are employed as writing instruments. Researchers have used this procedure to draw lines one molecule high and a few dozen molecules wide [45]. While specific applications for this technique are still being determined [13], it is expected to make a significant impact on molecular-based electronics as well as molecular diagnostics and catalysis [45].
- **Nanotweezers:** These are simply tweezers that can move nano-scale objects. Already demonstrated in laboratories, a pair of nanotubes growing on the end of a scanning-probe needle are opened and closed by an applied voltage. Used in conjunction with an appropriately powerful microscope, they have the capacity to allow construction and manipulation of nano-sized objects [29].

3.1.3.5 Nanotube-based sensors

The electrical conductance of semiconducting nanotubes is highly sensitive and very responsive to small concentrations of some gas molecules at room temperature (eg. nitrous oxide and ammonia). By comparison, conventional gas sensors for nitrous oxide and ammonia must be at temperatures over 400°C to function [46]. Therefore, nanotube-based chemical sensors could provide a significant enhancement to hazard detection. While 'bare' nanotubes are not sensitive to many kinds of molecules, nanotubes could be modified chemically or physically by dressing the tube in a thin layer of other molecules, (e.g. the development of hydrogen sensors by coating a layer of palladium on a tube [46]), to make sensors highly selective for a wide range of gases. Application of MWNT for detection of carbon dioxide, oxygen, and ammonia has also been reported recently [47]. US company Nanomix plans to introduce its first leak-detection sensors made from nanotubes shortly [34]. A conventional chemical sensor for detecting hydrocarbon leaks in a oil refinery costs about $3000, while a nanosensor could cost as little as $50 [34]. As such, nanosensors are extremely small, sensitive, energy efficient, and potentially, inexpensive [34], thereby having significant utility in military applications.

3.1.4 Current limitations

There are a number of technical obstacles that must be overcome before the potential of nanotubes can be fully realised and utilised in mainstream applications. Of course, depending on the maturity of the particular application, some such obstacles may have already been overcome. On the other hand, some difficulties may be too difficult to overcome and so alternatives may need to be sought. We have identified a number of such obstacles:

- Length of nanotubes: Currently, nanotubes cannot be manufactured of sufficient length to be used in developing super strong and lightweight composite materials; these are generally manufactured in the 1-10 microns range by most methods, or up to 200 microns by optimising nanotube growth [46] and rarely above 1 mm. Suggestions are that the preferred typical length of nanotube is several metres or more [23, 29]. However, this field is developing and changing rapidly, at least for nanotube-made threads. In the laboratory, the confirmed record length of nanotube-made threads is 30 cm [31], with recent reports suggesting that super-strong nanotube fibres up to 100 metres long have been created [8, 35, 48].
- Cost: The cost of nanotubes remains high. In 2000, the price of impure commercial nanotube soot was approximately $60 per gram, almost 10 times the price of gold [23, 29], while the price for SWNT was $1500 per gram [23]. By 2003, the price of MWNT dropped to $2 per gram, while the price of SWNT had halved [25]. The main reason for this is production cost. For instance, the three main fabrication methods of making nanotubes (plasma arching, chemical vapour deposition and laser ablation) are now relatively straightforward, while the main raw ingredient, carbon, is inexpensive [29]. The development of mass production techniques is one critical issue for improving affordability and availability. Certainly, the price of nanotubes is likely to reduce significantly as factories for producing MWNT (expected to produce 120 tons per year in 2003 [19]) come online. Similarly for SWNT, it is expected that by 2005 factories capable of producing thousands of kilograms of SWNT per week will be operating [34].
- Lack of bonding: Pure nanotubes appear to be too 'slippery' in manufacturing new composite materials. The extraordinary strength of nanotubes lies in the strong bonding between neighbouring carbon atoms. These carbon atoms are 'reluctant' to bind to other 'host' particles in composite materials. In practice, graphitic structures of nanotubes are made 'less' perfect in order to bond to other molecules (this is called functionalising the nanotubes) [29]. While nanotubes are being added to many

materials such as plastics[19], it has been opined that "there is still a long road ahead towards a practical, lightweight ultra-strong material based on nanotubes" [29].

- Manipulating nanotubes: Currently the capacity to mass-produce nanotube electronic devices is limited as there are no efficient techniques to position nanotubes in designated locations or orientations. The helicity (or chirality) of nanotubes [29], which defines how the graphene sheets are rolled into cylinders, cannot be controlled by current manufacturing techniques, meaning that the nanotubes produced are a mixture of conductors and semiconductors [37]. The helicity problem, in practice, is partially solved by culling conducting nanotubes using electrical means [25, 49]. If this problem is not overcome, it will be difficult to integrate nano-components (diodes, transistors, wires, etc.) into microcircuits.
- Storage capacity: Opinions regarding the capacity for nanotubes to store hydrogen are divided [42, 44]. The critical question yet to be answered is whether nanotubes have the ability to store hydrogen at 6.5% by weight under reasonable conditions of temperature and pressure. Opinion on this differs across the field.
- Responsiveness and relaxation: It has been found that nanotube-based sensors relax back to normal slowly after the source of target-gas is removed, which may mean they will not be sufficiently responsive [46]. In addition, it might be difficult to select the way of modifying the nanotubes for different target molecules.

3.2 Quantum dots

3.2.1 Introduction

QD are technically defined as small semiconductor crystals [50]. However, they are sometimes referred to as artificial atoms, due in part to the atom-like properties they possess, such as quantised energy spectra and being easily embedded in solid-state systems. QD are semiconductor boxes about 1 to 100 nm on a side [51], holding a number of electrons that may be altered at will [52]. As such they are not true atoms, as a typical QD contains in the order of 10^3 to 10^6 atoms embedded within a crystal lattice [53]. However some people define QD as semiconducting crystals whose size extends to a few microns and where the number of electrons is as high as several thousand [54].

3.2.2 QD properties

The attribute which has made QD the focus for development is that they are semiconductors whose shape, size and composition can be engineered artificially to have custom-designed properties [51]. QD can emit light (whether excited optically or electrically) in different colours simply by controlling its size. For example, a 3 nm QD made from cadmium selenide emits green light, while a slightly larger 5.5 nm particle of the same material radiates red light [55]. Indeed, a full spectrum of colours can be emitted from a single material simply by changing the dot size [56]. As such, they can be tuned to produce specific electronic and optical properties at the 'atomic' scale. Conductivity and wavelength of emitted light are tuned by doping (providing additional charge carriers by adding foreign atoms), optical excitation or external electric fields [53]. Recent developments suggest that by employing controllable electronic and optical properties of QD, these minuscule dots have much to offer in real-world applications from bio-applications to quantum computing [50].

3.2.3 QD Applications

3.2.3.1 Biological applications

Traditionally organic dyes and proteins, found in jellyfish and fireflies [55], are used for labelling in biological imaging techniques. These dyes need different colours (wavelength) of light to be excited [57]. Because of the relationship between QD size and colour, a mixture of the QD of different sizes can be excited by a single light source, allowing measurement and observation of several biological molecules or cells at the same time [55]. Moreover, organic dyes decompose whereas QD are stable [55]. Defence has an interest in using quantum dots in place of organic dyes used in biosensors [56] for portable biological warfare detection devices [50]. The bio-application of quantum dots is emerging with several start-up companies launching products into the market [50].

3.2.3.2 Optical applications

Due to QD's ability to produce light of a specified wavelength, these tiny crystals can be used in optical devices. Moreover, QD work well across a wide temperature range [50] and have a high efficiency in light emission [58]. Indeed, these optical properties are already being exploited for security tagging and anti-counterfeiting as QD produce colours which are hard to forge [59]. In addition, it is already possible to make light-emitting diodes[7] (LED) from QD [50, 56]. QD-based LED can be readily tuned to emit blue or green light, which is in the hard-to-attain, much-sought-after wavelength range [56].

Another application is chameleon-style camouflage [3, 36, 60]. It is predicted that by 2025 US will have adaptive combat clothing that changes its colours and patterns to mix-in with the environment [3]. Integrated photon-detector arrays can convert dominant optical signals (environmental electromagnetic emissions) into electrical signals that excite specific QD that emit light matching the surroundings. As QD can emit light throughout the visible light spectrum-from infrared to the ultraviolet [56], they can provide camouflage in both the visible and infrared regions of the electromagnetic spectrum.

3.2.3.3 Communications

Optoelectronic telecommunications is a hybrid of optical and electronic technology. Semiconductor-based light sources (such as LED and laser diodes) provide light for sending the data [39]. QD can be used in making optical amplifiers, waveguides, ultrahigh density optical memories and data storage, which are of vital importance in optical-communication systems [50, 56]. Indeed it is believed that "QD lasers would be less expensive and more efficient than current telecommunication lasers" [50].

[7] LED are semiconductor light sources that glow under an applied voltage and are used for colour display panels.

One QD property of particular use in communications is the ability to tune the wavelength of emitted light. This could lead to the development of an alternative blue-light laser, whose shorter wavelength permits higher densities of information storage in optical-communication systems [39].

Because QD are small more QD-based lasers can be assembled into photonic chips with the same sizes as in use today, or chips can be made smaller by using QD as semiconductor-laser materials. Indeed, it has been demonstrated that QD can make ultra-fast, all-optical switches and logical gates that work faster than 15 terabits a second, while the Ethernet can generally handle only 10 megabits per second [56].

The dot-based optical or optoelectronic devices applicable in communications are laboratory demonstrated but "commercial applications are unlikely to emerge in the next few years because of the industry's investment in entrenched technologies" [50].

3.2.3.4 *Quantum computing based on quantum dots*

Quantum computing is based on the premise that fundamental properties of matter (such as electron spin) can be employed to hold information in a similar way to standard computers. Quantum computing has an edge on traditional computers in terms of size (individual atoms and molecules providing the processing and storage). Its capacity to use a fundamental property of nature, quantum entanglement, allows it to run in effect as a super parallel computer, as each (atomic) node can represent multiple situations concurrently [61]. As a consequence, computational power increases exponentially, rather than linearly, when additional 'atomic processors' (or Qubits) are added. Using this idea of employing electron spin as the information carrier, computations can be performed by the manipulation of spins of electrons in QD [62].

The development of quantum computing constructed from QD is at a very early stage. Currently researchers are only able to detect the individual spins of each of two dots which are linked together by a 50 nm wide lines using electron-beam lithography [50]. However, given the potential benefits from this field we must continue to monitor the development of this field.

3.2.4 Current limitations

QD can be made either from clusters of atoms by colloidal synthesis [50], from thin semiconductor film by etching, by electrical squeezing techniques, or by epitaxial growth processes. However, the ability to produce commercial quantities at sufficient purity has yet to be realised [50].

While we may not be aware of all the developmental difficulties that might arise, some known obstacles need to be overcome prior to the commercialisation of QD applications. These include:

- **Quantity**: It seems that the current production rate is of the order of grams per week whereas commercial use in photonics or telecommunications would require hundreds of kilograms of QD material [50].
- **Quality:** While bio-applications require relatively small amounts of QD, they need to be of very high quality [50], and, as has been noted, "the most challenging obstacle is to achieve essentially perfect control over the size and purity of these nanostructures" [63]. In addition, a lot of QD materials are quite fragile, which requires further research to achieve long term stability and shelf-life [50]. Indeed, until this robustness issue can be overcome, most commercial applications of QD will be limited.
- **Technical maturity:** In some fields, such as quantum computing, research is currently at the 'proof-of-principle' level and therefore more speculative. As such, there are likely to be many unforeseen technical obstacles associated with the use of QD.

3.3 Nanostructured materials

3.3.1 Introduction

All materials are composed of some building blocks, called grains [22]. The key parameter that distinguishes nanostructured materials (powders or nanoparticles, metals, ceramics and other solids) from conventional materials is the size of the constituent grains. The diameters of grains range between 1 to 100 nm for nanostructured materials, whereas those for conventional materials are from microns to millimetres [64]. It is the size, complex interplay and interaction at the interfaces of grains that enable these nanomaterials to exhibit unique or improved mechanical, optical, chemical and electronic properties [65].

3.3.2 Nanostructured material properties

Nanotechnology is also likely to introduce a number of previously undiscovered properties of nature. For instance, gold nanoparticles of 2-3 nm in diameter have fundamentally different properties to the macroscopic properties because at the nanoscale level, properties such as the mean-free path of electrons is of the same order as the grain size of the nanoparticle [66]. On such small scales, it becomes reactive, its melting point decreases and even its colour changes (to red) [66]. As such, gold nanoparticles have applications that are new (eg. as a catalyst in chemical reactions). Therefore, as more nano-products are developed, new properties may allow novel applications that we may not initially be able to envisage.

The practical importance of nanostructured materials is through enhancement of:

- **Mechanical properties**: These materials have been engineered to have both high strength (or hardness) and ductility, two properties which have been mutually exclusive characteristics for conventional materials [67]. In addition, new forms of alloys, called 'hard metals', have been engineered to be as hard as diamond [68]. Conventional ceramics are brittle, while nanophase ceramics (such as nanophase titania) are ductile and are more sustainable than conventional metals in harsh environments of high temperatures and corrosive atmospheres [68]. Nanoparticle coating is the technique of dressing materials with thin layers of nanoparticles [22]. The coating can improve toughness and resistance to wear, corrosion, oxidation and cracks [68].

- **Optical properties**: As mentioned previously, one significant property of nanomaterials is their size. By controlling the size of constituent grains and surface structures, optical properties of nanostructured materials, such as reflectance and transmission of light, can be engineered [22]. For instance, while yttria, a conventional ceramic, is opaque, its nanophase counterpart can be made transparent because the tiny grains are unable to scatter (visible) light [64]. The tiny grains in such nanostructured materials can block (absorb or scatter) ultraviolet rays because of their much shorter wavelengths [64].
- **Chemical properties**: One new feature of the atomic arrangement in nanostructured materials is that a high percentage of atoms are at grain surfaces [68]. Because surface atoms are more reactive chemically than bulk atoms (atoms buried deep below), nanostructured materials also have utility in chemical processes.
- **Electromagnetic properties:** The giant magnetoresistance (GMR) effect is the phenomenon that electrical resistivity of certain materials varies markedly as the magnetic field varies [39]. Currently, GMR readout-heads in computer hard drives enable high-density data storage [39]. One class of nanostructured materials has exhibited GMR with changes in resistance 10 to 50 times larger than conventional GMR materials. This significantly improves the sensitivity of read-out heads and has the potential to create ultrahigh-density data storage devices [68].

3.3.3 Applications

The potential applications for nanostructured materials are extensive and so we only summarise them, focussing on novel mechanical, optical, chemical and electromagnetic properties.

3.3.3.1 Mechanical properties

In terms of mechanical properties:

- Materials such as 'hard-as-diamond' alloys can have use in the manufacturing of armour plate, jet-engine parts, drill bits and cutting tools [68]. It is reported that the use of nanostructured materials in aircraft can increase structural lifetime by as much as 300% [22];
- Malleable ceramics can be moulded into designed shapes, such as car parts which are cheaper and more durable in harsh conditions such as high temperatures and corrosive atmospheres than conventional metal parts [64];
- Nanocoatings on engine cylinders in motor cars can reduce heat loss and improve combustion of the fuel [22]. Coating for anti-corrosion and increasing chemical and thermal stability is important for the chemical and aerospace industries. Indeed, nanotechnology-based 'smart coatings' (with nanocapsules containing corrosion-inhibiting and self-healing chemicals) are under consideration for application on military equipment by the US Army [69];

- Nanoparticles are being considered for use in medical implants, such as for artificial heart valves [22]; and
- Nanoparticle reinforced polymers can make the armour of helmets and tanks 40% to 60% lighter [3].

3.3.3.2 Optical properties

In terms of their optical properties, nanostructured materials have a wide range of potential uses including:

- Nanocoatings can be designed to be transparent to visible light but opaque to the infrared. This would allow for self-cleaning smart glasses to better control heat, UV dispersion and light entering or leaving a building [22, 68, 70]. In addition, nanophase powders have been tested in cosmetics and in making transparent sunscreens [59, 64] and sun protection clothing [59]; and
- Nanophosphors[8] can improve the resolution of optical display units [22]. Nanoparticles may have military applications such as providing reactive camouflage, since the reflectance of light off an object depends on the surface structure (i.e. the patterns of nano-size features).

3.3.3.3 Biological and chemical properties

The potential chemical-based applications of nanomaterials are many.

- Nanomaterials can be very effective catalysts. For instance, nano-titania has been found to be five times more effective than conventional catalysts in promoting the removal of sulphur from simulated car exhausts [64];
- Nanocrystalline materials are used as separator plates in new generation batteries which require less recharging, and have longer life [22]. In one case, Nanometals, a Canadian technology-transfer agent, is developing nanophase alloys of nickel-molybdenum for use as advanced electrode materials for high-efficiency alkaline fuel cells [68];
- Nanoparticle silica 'paint' can be used to create surfaces which display anti-fog properties, and which are easier to clean and maintain [22];
- Biological and chemical sensors integrated in clothing for identification of bacteriological infections is imminent [16]; and
- Built-in chemical and biological protection layers through nanoparticle coatings that absorb or block hazardous chemicals or biological agents.

3.3.3.4 Applications based on novel electromagnetic properties

GMR-based ultra-high density data storage is being developed and within a decade, according to the staff of the US National Institute of Standards and Technology, will account for billions of dollars in annual sales for US companies [68]. High-power magnets can be made from nanocrystalline materials because of their large surface areas. These high strength magnets may have practical applications in the development of quieter submarines, automobile alternators, and land-based power generators, for example [22].

[8] Phosphors are materials for making pixels whose size determines the resolution of a television screen.

3.3.4 Current limitations

The area of nanomaterials is the most mature nanotechnology field [15, 19]. Indeed, the technical risk seems lower than in other fields if statements from those working in the field such as "there's no one big hurdle that needs to be overcome anymore; rather, there are many hurdles in each individual development effort, since each material has its own chemistry and its own set of problems to be solved" [68] are to be believed. Certainly, efforts in broadening the range of nanomaterials, enhancing the ability in grain-size control and improving production quantity and quality in industrial scale are being pursued. Generally, some known barriers are:

- **Cost**: Costs have to decrease if commercial industrial applications are to be achieved. There are more than 30 different processes to manufacture nanomaterials and many of them are expensive. However, with new manufacturing processes being developed, the price of nanomaterials is decreasing. For instance, through new manufacturing technologies, US company Nanophase Technology reduced the price from $1000 to $0.10 per gram between 1989 and 1997 [68].
- **Production rate**: Some further development to support large-scale manufacturing is necessary as many processes have been generally at small scales in laboratory settings [68].

4. Nanodevices

4.1 Miniature electromechanical devices

4.1.1 Introduction

Electromechanical systems (EMS), regardless of scale, generally comsist of two integrated components. The mechanical parts include moveable structures such as mirrors, beams, cantilevers and gears [22, 71, 72], which respond to applied forces by deflection or vibration. The electronic elements, such as small motors and integrated circuits [22, 73], act as transducers to transform mechanical motion into optical or electrical signals and vice versa [72]. Scaling these down, there are two distinct levels of EMS: MEMS and NEMS, the technical attributes and potential applications of which we review below.

MEMS have been studied for decades and are now finding increasing application in industrial and commercial sectors [73]. While MEMS technology is technically outside the nanotechnology domain, we include it as many researchers consider it as an integral part of the nanotechnology field [17]. Indeed, it is expected that the functionalities shown by MEMS could also be performed by NEMS [22]. So while there are some distinctions (as noted in section 4.1.3), the technical maturity of MEMS provides some short-term potential and some insights into long-term trajectories for NEMS.

On the other hand the field of NEMS is in the earliest stages of research and development, generally at the laboratory level. Indeed, our literature search only uncovered four NEMS review articles from two distinct sources [49, 72, 74, 75]. Therefore the application prospects of NEMS are somewhat limited and are yet to be addressed in popular science and technology magazines such as *New Scientist* and *Scientific American*. Compared with the more mature MEMS, the few NEMS devices that have been identified are likely to face a number of technical hurdles before application is realised.

4.1.2 MEMS

4.1.2.1 Technical attributes

MEMS is fast becoming a mature field with prototypes already in the marketplace, generating $3.4 billion in sales globally in the year 2000 and expect to be $31.5 billion by 2010 [22]. The advantages provided by MEMS include low power, low mass, low cost and high functionality [1]. With the integration of sensors, actuators and computer circuitry, MEMS can sense and measure environmental changes caused by pressure, light, motion, electromagnetic signal and chemicals, and make decisions and act on the information received [73]. MEMS have been used for automotive pressure sensors for pollution control, disposable blood pressure sensors, and accelerometers for car airbags [73].

MEMS devices are largely manufactured by photolithographic micro-machining techniques (similar to those used for making integrated circuits) to integrate mechanical and electronic parts on the surface of a silicon chip [73]. Progress in the fabrication of optical MEMS by self-assembly techniques (techniques where micro-components are assembled into a desired pattern autonomously) has been reported [76].

4.1.2.2 Applications

We note that the potential application of MEMS to defence has been recently reviewed within DSTO [77]. That report focussed in detail on MEMS research published in the period 1999–2000. The discussion of potential MEMS applications in the defence arena covered a wide range of topics, such as micro aerial vehicles, MEMS switches and micro relays in communications, micromotors. Therefore we only provide an overview.

The following generic MEMS applications are noted in the literature:

- **Physiological status monitoring**: Researchers are developing MEMS-based biofluidic microprocessors to continuously monitor an individual soldier's physiological parameters to provide ongoing assessment of a soldier's medical condition and even to deliver immediate, responsive treatment [78].
- **Medical diagnostics and chemical analysis sensors**: Absorption of molecules on a microbeam can alter the mass of the beam and therefore the beam's vibrational frequency. MEMS sense the existence of some chemicals by detecting the changes in vibrational frequency of micro-beams [71]. MEMS sensors might consume only 20% of the operating power of current devices and be integrated into soldiers' masks or equipment [1].
- **Electronic display control devices**: Electrically controlled micro-mirrors reflect light directly onto display screens to illuminate either pixels or pictures elements [71]. This

provides for high resolution, brightness, and large screen display. It might also be possible to employ such devices for small head-mounted monocular displays [1].

- **High-density data storage systems**: Two applications of MEMS are Scanning Tunnelling Microscopes (STM) and AFM [79]. Originally, STM and AFM were designed to 'see' and manipulate individual atoms on an object's surface using a needle-like probe [39]. With an array of such probes applied to the surface of an appropriate storing medium, binary data can be stored by creating a dent for 1 and no dent for 0 [79]. As the size of a dent is at atomic scale, the storing density could be very high. A postage stamp-size memory card with several gigabytes storing capacity is expected by 2005 [79].
- **Aerodynamic control**: MEMS-made 'smart skins' (consisting of sensors and movable tiny plates) could be applied to the wings of aircraft. Sensors could then monitor airflow near the wing, and adjust positions accordingly. This would produce an enhanced aerodynamic-control, which would enable an aircraft to turn more quickly and withstand turbulence [71].
- **Invisibility:** One highly speculative suggestion (from the Institute for Soldier Nanotechnologies) is that the integration of micromechanical sensor arrays with interweaved organics polymers can "reproduce the light that would pass through as if the soldier was not there, creating an effect *approaching* invisibility" (our italics) [80].

In the military sphere, Defense Advanced Research Projects Agency is supporting research and development into applications [78] such as:

- MEMS radio-frequency switches to augment existing military surveillance, communication and radar-ranging satellites. Two prototype picosatellites (weighing 250 grams each) launched in January 2000 used such technologies;
- Construction of a 'smart' fusing and arming device in anti-torpedo weapons;
- Improved ruggedness and survivability of land equipment in the development of shock-resistant instrumentation for munitions or projectiles;
- Embedded tyre-pressure sensors for armoured vehicles to monitor tyres for signs of deterioration and possible blowouts;
- MEMS-based sensors and transmitters to enhance the information exchange between commanders and soldiers by providing individual geo-location and physical status data;
- MEMS sensors to be employed for protection against biological and chemical weapons by providing fast detection, diagnostics, and potentially automated methods of treatment.

4.1.2.3 Current limitations

Given the level of maturity of MEMS, there appears to be little discussion in the literature about fundamental hurdles in its realisation. However, there is always the potential for "unexpected obstacles on the road from a proof-of-principle experiment to a working prototype and then on to a product that succeeds in the marketplace" [79]. Generally speaking, it is a challenging task to scale up manufacturing of laboratory-demonstrated devices to industrial-scale mass production [73].

4.1.3 NEMS

4.1.3.1 Technical attributes

Although NEMS are much less technically mature than MEMS, they should provide many applications not achievable with MEMS. Besides having many of the attributes of MEMS, NEMS have extra advantages derived from their smaller sizes leading to [72, 74]:

- Higher natural frequency of mechanical parts of NEMS which means a faster response to applied forces;
- Higher quality or Q factor of resonance, which results in lower energy consumption and suppressed thermo-mechanical noise; and
- Smaller effective mass of the vibrational parts, which gives extremely high sensitivity to additional mass.

4.1.3.2 Applications

Due to their scale relative to atomic and molecular structures (and in addition to those applications described for MEMS), NEMS are likely to prove to be useful for sensing and measurement. As such, some potential NEMS-specific applications are [49, 72, 74, 75]:

- Measurements of force or displacement in fundamental science and metrology;
- Magnetic resonance force microscopy to image individual molecules with atomic-scale resolution;
- Fast logic gates, switches or mechanical computers;
- Non-invasive medical diagnostics;
- Highly functional mass/force sensors;
- Displays; and
- Ultrahigh-density data storage.

One example of the potential military application of NEMS technology is the concept of 'surveillance dust', inexpensive, ultra-miniature NEMS- or MEMS-based sensors to monitor sensitive areas on the battlefield [30]. We note that the associated NEMS or MEMS components must be cheap for the concept to be plausible, considering that the number of MEMS/NEMS particles in a dust must be huge. However, it has been suggested that given that the manufacturing process for these are similar to those used in making integrated circuits, cheap MEMS or even NEMS should be possible; this is a major advantage of NEMS and MEMS technology [1].

4.1.3.3 Current limitations

It has been noted that, technically, there are three significant obstacles that need to be overcome in order to realise the full potential of NEMS.

- **Instability:** Having high-sensitivity means that NEMS have a propensity for instability, as they are designed to be responsive to atoms and molecules. In cases where gaseous atoms or molecules are present, natural fluctuations may constrain the application of NEMS [49, 72].
- **Interaction between nano- and macro-world:** Interaction between the nano- and macro-worlds is not trivial. Transducers in NEMS act as messengers for transferring information from nanoscale up to the macroscale and feedback and control back down.

As such, they need to be sufficiently sensitive to resolve displacement of mechanical parts in the picometre to femtometre (10^{-12}m – 10^{-15} m) range, across a very large bandwidth (up to a few gigahertz frequencies) [49, 72]. To further complicate the situation, most of the transduction techniques used in MEMS are not applicable at the nanoscale [72]. Therefore, building transducers for NEMS that satisfy these two requirements is a significant challenge.

- **Novel physical properties:** A challenge at the fundamental level of science is to deepen understanding of the physics of surface atoms. As devices shrink further and further, surfaces will play a more and more important role in dominating physical properties. Understanding the roles played by surface atoms continues to be a major challenge [49, 72].

4.2 Nanobots

4.2.1 Introduction

Nanobots are possibly the most controversial of the potential applications of nanotechnology. Often referred to as assemblers, nanobots are based on the concept of a molecular machine that can assemble almost any structure (including copies of itself) from the bottom up, by placing individual atoms in specific positions. Significantly, this property means that it can self-replicate if so programmed [81]. Drexler, one of the leading proponents of nanobots, introduced the assembler concept in his 1986 book *Engines of Creation* [14] and responded to criticism of the feasibility of this concept in his 1992 book *Nanosystems* [82] which has not been well received by some in the field [83].

4.2.2 Technical attributes

MEMS and NEMS are mainly fabricated through a 'top-down' approach where miniature (micro or nano) devices are carved out of a block of material [84]. Nanobot construction takes the opposite approach. Here, nanofabrication is 'bottom-up', with tiny devices (nanobots) built up by arrangement of atoms or molecules into designated positions via self-assembly processes. In a self-assembly process, atoms or molecules form functional devices autonomously to minimise free energy [22, 85].

The basis for the nanobots (or assemblers) concept is that:

- There exist molecular machines in nature. Cells reproduce themselves each time they divide. Cells contain the organic machinery (ribosomes), which build various protein molecules by 'reading' instructions transcribed in RNA. Ribosomes are proof that nanomachines built of protein and RNA can be programmed according to information stored in DNA to build complex molecules [14].
- Use of self-assembly methods by which ordered and functioning objects can be formed from atoms and/or molecules through chemical reactions [85]. It has been reported that a self-assembling process using DNA has formed tiny motors, tweezers and pistons [86, 87].

- With the help of tools such as STM and AFM, scientists are able to pick up atoms one by one and to arrange them in a pattern, a process that could be automated along the lines of a biological process.

4.2.3 Applications

According to Drexler [88, 89], some of the benefits of these future, self-replicating, programmable assemblers include:

- Manufacturing products with greatly improved properties at a very low cost;
- Destroying virus and cancer cells;
- Cleaning the environment;
- Repairing damaged tissues and cleaning the arteries; and
- Reviving bodies preserved in cryogenic storage by fixing damaged brains and organs.

From the military perspective the impact of future nanobots is considerable if statements such as "an enemy force could be devoured in a few hours by near-invisible hordes of trillions of such self-replicating robot" [30] are to be believed. Indeed, the realisation of such a concept might constitute a new form of a Weapon of Mass Destruction.

At a more practical level, application to the field of biomimetics (which focuses on the development of materials or structures by mimicking biological systems [90]) has some potential. In this case, materials such as artificial bones or teeth can be manufactured to order through self-assembly from seed molecules or crystals [16].

4.2.4 Current limitations

As we have noted, there are a number of technical issues that must be overcome before a proper appreciation of the application and utility of nanobots can be properly addressed. Some of the technical issues that have come to light thus far are:

- Fat fingers problem – There may be insufficient space at the nanoscale for the atomic-sized pick-and-place pincers of nanobots to manipulate atoms effectively [91];
- Sticky fingers problem - In order to manipulate the atoms to build nanoscale structures, nanobots pick up components by adhering to them. It may prove difficult to then release those atoms to the desired sites [91];
- Power – It is unclear what mechanism might be used to power nanobots [83];
- Communication - Instructing nanobots from the macro-scale may be technically difficult [83];
- Thermal noise /Brownian storming – Collisions with external molecules (whether gaseous or liquid) could lead to random (Brownian) motion in nanobots making this extremely difficult to control [92];
- Quantum mechanical effects – fundamental quantum properties (such as Heisenberg's uncertainty principle) may render nanomachines ineffective beyond a given scale; there is a fundamental limit on the precision that might be achieved [14, 93].

4.2.5 Health warning

The field of nanobots is very much in the conceptual stage with little more than basic research being undertaken. As such, the feasibility of the nanobot concept remains uncertain. Scientists can build structures with atoms either by self-assembling or with tools like STM, the idea of nanobots does not violate existing physical laws and, indeed, self-replicating nanomachines do exist in nature. However many critics question Drexler's assembler concept [83, 91, 92]. The concept is still controversial and is considered as a futurist's daydream by its opponents [12, 94]. Some efforts have been made to address these concerns [14, 81, 82, 93, 95, 96] (although not entirely successfully [83]), such as employing computer simulation techniques to prove the theoretical feasibility of nanobots and using the existence of biological molecular machines to show the technical feasibility. Taking all this into account, we note that the concept of nanobots needs to advance beyond the drawing board before being considered within feasible technology concepts.

5. Some nanotechnology applications and indicators

The level of maturity of the nanotechnology fields varies from near mature to highly speculative. It is important, then, to have some sense of how such technologies might be applied and to identify those characteristics that can indicate the viability and feasibility of a particular technology. Therefore, we use some of the nanotechnology properties discussed previously to suggest some technology applications. In addition, we propose key indicators towards the realisation of these along with suggested levels of feasibility. We note here that it is a challenge to list key indicators for those potential applications demonstrated in principle in laboratories. For instance, while it is experimentally demonstrated that nanotubes could be used as wires or transistors, it will still need a sustained effort to design architectures to interconnect these parts into circuits that can plug into a computer or other system.

5.1 Nanotubes

Table 1 shows some prospective nanotube applications, suggested realisation indicators and levels of maturity. The characteristic properties indicate that nanotubes are likely to have applications in a large number of areas, including functional clothing , advances in circuitry, and nanoscale probes and sensors. Indeed, nanotubes are likely to be an enabler for the development of other nanotechnologies (and in other fields such as biotechnology). In many cases the capacity for reliable and inexpensive mass-production techniques is the limiting factor. In others, the capacity to control such devices needs some further work.

Table 1: Potential nanotube applications and indicators for realisation

Outstanding properties	Indicative applications	Key indicators	Level of maturity
Extraordinary resilience and tensile strength	*Ultra-strong, lightweight fabrics*	Invention of economical, efficient production methods for long and/or high purity nanotubes. Invention of efficient and economical techniques to functionalise nanotubes so that these tubes can be bonded into host materials.	Speculative
Excellent field emitting ability	*Lighting and display*	Demonstrated cheaper price and better quality to compete with other lighting and display techniques.	Emerging
Excellent thermal conductors and potential electrical semiconductors	*Wires, transistors, diodes*	Substantially enhanced ability to manipulate the position and orientation of tubes. Development of efficient methods to control or select the helicity of nanotubes.	Laboratory demonstrated
Hollow-centre structure	*Hydrogen storage in fuel cells*	Solid confirmation of nanotube's capability of hydrogen storage. Invention of efficient and economical production method of nanotubes.	Speculative
Mechanical strength at small scale	*Probe tips for scanning microscope*	More efficient manufacturing would be desirable.	Matured.
Electrostatic properties	*Nanotweezers to pick up and move nanoscopic objects*	Important for fundamental scientific research. The impact on technology is generally indirect.	Laboratory demonstrated
Electrical conductance very responsive to small concentration of some gas molecules	*Highly sensitive and rapidly responsive chemical sensors*	Progress in understanding of the interactions between nanotubes and gas molecules.	Emerging

5.2 Quantum dots

The capacity to create desired 'molecular' properties means that QD are likely to have a significant impact, if they can be realised in an efficient manner. As Table 2 indicates, the tuneable optical properties are likely to find application in optoelectronic and digital systems. Some options for potential applications are emerging, however until the manufacturing process becomes more robust, commercial applications are limited. Of course, QD may provide one basis for the development path of quantum computers. However, there remains a great deal of uncertainty as to how such systems would be built, operated and maintained. Indeed, it is likely that it will be necessary to integrate scientific developments from a number of different scientific fields in order to achieve the required functionality. In effect, the concept of integrating QD within quantum computers remains speculative.

Table 2: Potential QD applications and indicators for realisation

Outstanding properties	Potential applications	Key indicators	Level of maturity
Tuneable optical properties	*Biological labelling, biosensing*	Progress in the development of efficient manufacturing process in mass production and perfect control of the size and purity of quantum dot materials.	Emerging
	Light-emitting diodes for illumination, display and camouflage		Emerging
	Laser diodes, optical amplifiers and switches, logic gates for optical communications		Laboratory demonstrated
Electronic spins as information carriers	*Quantum computer*	This area is largely in the realms of basic research. Therefore the basis for constructing and operating quantum computer remains to be resolved. Indeed, its commercial viability is yet to be proven.	Speculative

5.3 Nanostructured materials

This emerging field within nanotechnology is built around the unique mechanical and optical properties that nanostructured materials display. These can be harnessed to produce materials that outperform conventional ones in terms of strength, weight and durability. Their scale means they can be integrated within macroscopic systems to deliver very particular and/or precise effects. Again, manufacturing issues are the key indicators to their commercial realisation. However, as noted previously, significant advances in this area have already been achieved.

Table 3: Potential nanostructured material applications and indicators for realisation

Outstanding properties	Potential applications	Key indicators	Level of maturity
Extraordinary mechanical properties: high strength and ductility, more durable in harsh environment	*Novel armour plates, jet-engine parts, cutting tools and drill bits, medical plants, coating*	Improved or novel techniques in the manufacturing of nanoparticles in industrial scale. The enhanced ability to control the grain-size.	Emerging
Extraordinary optical properties: able to absorb or scatter light selectively by controlling their grain sizes.	*Cosmetics, sunscreens, High-resolution displays, camouflage*		Emerging
High surface-to-volume ratio of building blocks.	*Very effective catalysts in chemical reactions, biosensors, more effective fuel cells and long-lasting batteries*		Emerging
Exhibiting GMR effect.	*Ultra-high density data storage*		Emerging

5.4 Nano-devices

As Table 4 indicates, the impact of nano-device applications on the military are likely to be both 'incremental' and 'disruptive' in nature [97, 98]. There has been some evolutionary development in the production of 'miniature' devices that perform the same functions as conventional devices but in a far more efficient way, thus providing an incremental improvement. In addition the capacity to have functioning devices at such small scales means that these devices can be used in areas where previously it was impossible due to size considerations. This suggests that the functionality NEMS will provide will largely be an enhancement on MEMS. However, it is conceivable that NEMS and nanobot devices can be constructed to replicate and operate independently. This would have serious consequences in terms of both offensive and defensive applications, and so potentially revolutionise military activities. Therefore, while the capacity to realise such devices is quite contentious, any further indications as to their likely realisation will raise a number of social, cultural, political and ethical issues. Indeed, it will eventually be necessary to develop international protocols and conventions for the acceptable use of such technologies.

Table 4: Potential nano-device applications and indicators for realisation

Outstanding properties	**Potential applications**	**Key indicators**	**Level of maturity**
Light, cheap, low power-consumption high functionality	*Sensors, high-resolution display, high density storage, aerodynamic control*	Efficient mass-manufacturing techniques to scale up laboratory-demonstrated applications would be desirable	Matured/ Emerging
As above, but with higher sensitivity and lower power-consumption.	*As above, but especially for tools in sensing and measurements at the molecular scale*	Invention of effective methods to enhance stability of NEMS. Development of novel techniques of efficient transduction in NEMS.	Laboratory demonstrated
Self-replicating programmable robot-like nanomachines	*Build or destroy anything atom by atom*	Many fundamental barriers exist (see the main text)	Highly speculative.

6. Possible impact of nanotechnology on land warfare

The intent of this work is not only to give an overview of nanotechnology, but also to provide some appreciation of the utility of nanotechnology to future land warfare. We investigate the battlespace effects of nanotechnology by examining the likely influence nanotechnology might have on the generic capability of the Army. To achieve this, we assess how nanotechnology can help in the development of Army's capability by considering the Army as a set of seven inter-related core skills: engagement, information collection, decision making, movement, sustainment, communication, and protection [9, 10]. This section presents the outcome of our analysis. In order to determine the priority of technology based variables (TBV), we denote:

- (*) to signify elements which are of 'routine importance';
- (**) to designate 'high payoff' attributes; and
- (***) to denote those attributes which are 'critical', and as such are likely to have the greatest impact on capability.

The priorities of TBV were defined and determined by influence diagrams [9].

6.1 Engagement

The most probable initial impact that nanotechnology will have on the engagement core skill is through the fielding of lighter weight and/or stronger systems, as indicated in Table 5. This would either make the combat system more agile or allow it to have greater firepower. Indeed, one significant issue that remains to be resolved within the current Soldier Combat System modernisation activities (Land Warrior in the US and LAND 125 in Australia) is weight. It is expected that an individual Land Warrior Mk I system will weigh approximately 40 kg, and there are concerns about the additional weight burden such a system may place on the individual soldier [36, 99]. Importantly, some involved within that program have suggested that the Land Warrior system has already exhausted all benefits that traditional lightweight composite materials can offer [99]. Nanotechnology may provide an opportunity to overcome these constraints. Weight issues can be overcome with both new armour materials based on nanotube-thread fabrics, and by use of nanotubes to miniaturise electronic and photonic elements, memory hardware in computer/communication and display. In addition using nanotube-enhanced plastic wires may also deliver a reduction in weight.

Table 5: Possible nanotechnology applications for engagement

<table>
<tr><th>TBV
(*) – routine
(**) – high payoff
(***) - critical</th><th>Key Technology features</th><th>Possible Nano-enhancement</th><th>Relevant Nano-areas</th></tr>
<tr><td>Blue safety (**)</td><td>Low signature due to reduction of vehicle weight.</td><td rowspan="4">Nano-reduction of weight of vehicles:
1. Lighter and stronger Nanoarmour of vehicles
2. Improved performance of fuel cells
3. Greater battery lifetime</td><td rowspan="4">Nanoparticles
Nanotube-enhanced materials</td></tr>
<tr><td>Blue weapon ability (*)</td><td>Blue range - extra weapon carrying capacity.</td></tr>
<tr><td>Usage rate (*)</td><td>Sustainment - extra ammunition carrying capacity.</td></tr>
<tr><td>Blue targeting ability (**)</td><td>Blue reach</td></tr>
<tr><td>Blue positioning (**)</td><td>Blue geolocation.</td><td>MEMS/NEMS-based sensors and transmitters</td><td>MEMS/NEMS</td></tr>
</table>

6.2 Sustainment

As indicated in Table 6, nanotechnology can enhance the sustainment capability of the future Land Force. Most impacts are likely to be secondary effects, such as lighter or more durable vehicles requiring less sustainment and maintenance. The implications of nanotechnology for sustainment should not be under-estimated, as the future battlespace is likely to require a significantly higher power supply. For example, Land Warrior Mk I systems are very power-intensive. Currently they use non-rechargeable lithium-ion batteries that are only capable of providing 12 hours uninterrupted supply [99, 100], even though the stated minimum requirement is 30 hours [36]. Any capacity to reduce the energy load through lighter vehicles or more efficient systems, or to produce smaller, longer life power sources is likely to give that force greater opportunities. Of course, in some respects, nanotechnology may create an additional burden since there may be the necessity to repair and replace nano-devices in-theatre. The skills and equipment required to perform such functions may not be manageable in such circumstances. Therefore, mass-produced, disposable devices are likely to provide the greatest opportunities here.

Monitoring soldier health would also be enhanced through nanotechnology if used in conjunction with bio-, information and communication technologies. This would provide the capacity to monitor, sustain and maintain soldier capability during operations, improving both the physiological capacity of soldiers and their survival rates.

Table 6: Possible nanotechnology applications for sustainment

TBV **(*) – routine** **(**) – high payoff** **(***) - critical**	**Key Technology features**	**Possible Nano-enhancement**	**Relevant Nano-areas**
Wastage rate (**)	Ruggedization	Nanoarmour	Nanoparticles Nanotube-enhanced Materials
Knowledge of requirements (*)	Knowledge management	Ultra-high density data storage for computer databases	Nanoparticles, MEMS/NEMS, QD-based ultrahigh-density optical memory and data storage
	Machine functions investigation	Nanosensors	MEMS/NEMS, Nanoparticulate coating
	Personal health status	Biosensors MEMS/NEMS-based diagnostic techniques	MEMS/NEMS, nanotube, QD, Nanoparticles
Efficiency of usage (**)	Low usage rate	Nano-reduction of weight of vehicles More durable equipments made by nanoparticles or dressed by nanocoating	Nanoparticles

6.3 Protection

The use of nanotechnology has a number of implications for protection, shown in Table 7. One might suggest that this is the area most likely to immediately benefit from nano-technology. The mechanical, optical and electronic properties of nanomaterials might all be used to great benefit. Lighter, stronger armour will enhance survival rates. Nanocoatings can be used to enhance camouflaging and so reduce the electromagnetic signature of many military systems. Shielding of electro-magnetic devices would allow systems to remain undetected, as would miniature sensors. Nano-scale biosensors would give warning against biological and/or chemical weapons. Ultimately, nanotechnology may significantly reduce the need to put soldiers in dangerous situations.

Table 7: Possible nanotechnology applications for protection

TBV **(*) – routine** **(**) – high payoff** **(***) - critical**	**Key Technology features**	**Possible Nano-enhancement**	**Relevant Nano-areas**
Inherent blue signature (**)	Reduced signature	Nanocoating.	Nanoparticles
Information acquired by blue of blue (***)	Blue positional information	MEMS/NEMS-based sensors and transmitters.	MEMS/NEMS
Blue self defence against red actions (*)	Active defence	MEMS/NEMS or nanotube-based or QD-based biosensors, chemical sensors or seismic sensors.	Nanotubes, MEMS/NEMS, QD.
	Passive defence	Lightweight and/or super strong nanoarmour; Nanotube-enhanced fabric; Nanotube-based electromagnetic shielding of communication systems.	Nanoparticles Nanotubes
Protection against the environment (*)	Vehicle protection	MEMS/NEMS, nanotube-based or QD-based chemical sensors in mine detection; equipments made by nanoparticles or dressed by nanocoating.	Nanoparticles, Nanotubes, QD, MEMS/NEMS
	Personal protection	MEMS/NEMS, nanotube-based or QD-based biosensors or chemical sensors, personal armour, MEMS/NEMS-based diagnostic techniques.	MEMS/NEMS, Nanotubes, QD

6.4 Movement

As shown in Table 8, nanosensors and nanoarmour may enhance the movement skills of the future Land Force. Miniaturisation of equipment means that vehicles can carry more (requiring fewer vehicles), have greater range, move faster, or have greater opportunities for use (as their weight is no longer a limitation on how they are deployed). In addition, nanosensors would enhance navigation.

Table 8: Possible nanotechnology applications for movement

TBV **(*) – routine** **(**) – high payoff** **(***) - critical**	**Key Technology features**	**Possible Nano-enhancement**	**Relevant Nano-areas**
Carrying capacity per vehicle (***)	Miniaturisation	Nanosensors Minute communication systems	MEMS/NEMS, QD Nanoelectronics
	Power management	Low power usage devices such as a nanotube-based display	Nanotubes
Vehicle range and speed (*)	Light weight vehicle	Nanoarmour	Nanoparticles, nanotubes
Navigation capability (**)	Navigation aids	Nanotube-based display, MEMS/NEMS sensors	MEMS/NEMS, nanotubes
Breakdown rate (*)	Reliability	Automatic diagnostics by MEMS/ NEMS and more durable equipment	MEMS/NEMS, nanoparticles

6.5 Information collection

It is likely that nanotechnology will support the development of information collection capabilities. As shown in Table 9, this will include enhancing the functional capacity of detectors and through the fusion and presentation of that information. Certainly, the ability to deploy large numbers of essentially undetectable and durable unattended sensors (as suggested by the 'surveillance dust' concept) is highly desirable. However, for these to be effective, integration with Information and Communication Technology is essential. Some nanotechnologies, such as QD, may provide a unique opportunity to collect data as optical wavelengths that are currently difficult to access. This would certainly enhance detection capability. Novel displays and approaches to computing are also potential candidates for nanotechnology enhancements. In addition, any improvements to data compression would be advantageous. However, this implies better data management and utilisation strategies.

Table 9: Possible nanotechnology applications for information collection

TBV	**Key Technology features**	**Possible Nano-enhancement**	**Relevant Nano-areas**
Information fusion and analysis (**)	Novel display techniques Novel information processing systems such as optical or quantum computers	Nanotube or QD based lighting and display, novel information processing techniques	Nanotubes, QD
Volume covered per unit time by sensor (*)	Capability of vehicles; Angular coverage of detection; Efficiency of detection; Range of sensors Capability of unattended sensors	MEMS/NEMS, nanotube or QD-based sensors	MEMS/NEMS Nanotubes, QD
Wavelengths covered by surveillance systems (*)	Sensor capability	Nanosensors, QD	MEMS/ NEMS, nanotubes

6.6 Decision making

As indicated in Table 10, initially at least, nanotechnology will have only a limited direct impact on decision making. However, any enhancements to other core skills (especially communication and information collection) are likely to have significant indirect effect effects. In addition, if applications such as rapid prototyping were realised, the impact on the decision cycle would be significant.

Table 10: Possible nanotechnology applications for decision making

TBV	**Key Technology features**	**Possible Nano-enhancement**	**Relevant Nano-areas**
Manipulation of information (**)	Visualisation	Nanotube-based display	Nanotube
Pool of stored information (**)	Data libraries	Ultrahigh-density data storage	NEMS, nanoparticles, QD

6.7 Communication

As Table 11 shows, nanotechnology provides a number of opportunities to improve communications capabilities. This is likely to take the form of augmentation to other Information and Communication Technologies, although we cannot exclude the possibility that devices largely built around nanotechnologies will be useful in their own right. Certainly any form of miniaturisation of transmitters will be beneficial, especially with an increasing prevalence of autonomous and semi-autonomous systems operating in an increasingly distributed battlespace. In addition, any nanotechnology-inspired enhancements to the encryption of data would be advantageous within the digital battlespace envisaged for the future.

Table 11: Possible nanotechnology applications for communication

TBV **(*) – routine** **(**) – high payoff** **(***) - critical**	**Key Technology features**	**Possible Nano-enhancement**	**Relevant Nano-areas**
Targeting to right addresses (**)	Limited broadcast techniques	Broad applications from nanotechnology in communication, such as the use of quantum dots in optical communication and quantum computing.	
Environmental propagation (*)	RF broadcast carriers; Relays		
Individual site to site link capacity (*)	Compression; Digitisation; Receiver management		
Vulnerability to red force disruption (**)	Non-broadcast transmission; RF broadcast carrier		
Blue susceptibility to intercept (**)	Encryption; Non-broadcast transmission; Line of sight narrow beam transmission; Disguised transmissions		

6.8 Summary

Overall, this analysis indicates that nanotechnology will have a broad range of influences across all seven cores skills of the Army by providing novel sensors, new armour materials, high-density data storage and new types of computers. Indeed, one scientist with the US Soldier Systems Center has stated: "we are in the early stages of anticipating how nanotechnology will revolutionize army equipment. Research in the field is already showing tremendous promise" [3].

7. Summary

The increasing importance of nanotechnology (as noted by the increasing levels of funding) means that we must have some appreciation of what it consists of, the trajectories along which is might develop and how these might impact and change the ways we operate. The field of nanotechnology covers a vast range of endeavours, from which we have focussed on four major themes: nanotubes, QD, nanostructured materials and nano-devices. These areas are at differing levels of maturity (both internally and externally) and face a number of obstacles, as we have indicated in the text. Most prominent are the ability to mass-produce robust, high quality components in a cost effective manner. While there is some evidence that this is occurring, it is inconsistent and uncoordinated. We also have noted the relevance of nanotechnology to the military sphere, through an investigation of how particular nanotechnologies might help in modernization of kit and in the enhancement of Army core skills through the provision of such components as new types of armour, sensors, and communication equipment. Finally, we note that there are a number of challenges in performing such a study. Nanotechnology is a large, emerging and rapidly evolving technology domain. As such there remains some uncertainty how it will evolve and into what specific applications. Indeed, its potential integration with other emerging technology fields (such as biotechnology) suggests that some significant applications are yet to be recognised. As such, our study aims to provide a general impression of where some impacts of nanotechnology are likely to be felt within the Land Force. Therefore this activity is ongoing and will be continually updated and critiqued as new information arrives.

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19. ABSTRACT

This report presents the review of progress in selected nanotechology topics and some possible applications. We survey four major branches within the field: nanotubes, quantum dots, nanomaterials and nanodevices. For each of these, we review the underlying scientific concepts, potential enabling technologies and current limitations to the realisation of nanotechnology applications. Possible implications for the future Land Force are discussed by examining potential nanotechnology impacts across seven core military skills within the Army-as-a-System construct.