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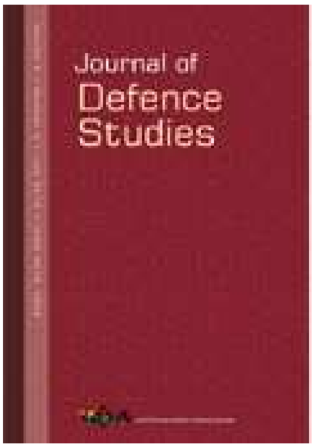

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Nanotechnology

Current Global Trends and Future Military Applications for 'Soldier as a System'

Sanjiv Tomar*

The last decade has witnessed unprecedented developments in the discovery of novel materials and their radically different properties at nanoscales. Global efforts in research and development (R&D) in nanotechnology are being undertaken by many countries due to far-reaching benefits encompassing the entire arena of science and technology. The field of defence is likely to profit immensely by nanotechnology-enabled applications. The impact of these applications will have a direct bearing on soldier in the battlefield in terms of enhanced protection, lethality, manoeuvrability, communication, health monitoring, and surveillance. This article dwells upon the current global scenario of nanotechnology and how a 'soldier as a system' can be conceived through integration of nanotechnology-enabled applications.

Introduction

Nanoscience and nanotechnology are the fast-growing areas of science and technology that span the entire spectrum of science and technology.[1] Though it is the study of phenomenon at nanometre[2] (nm) scale, there is no strict 'definition' of nanotechnology as on date, possibly due to the large spectrum of scientific disciplines it covers. Besides, nanotechnologies at the current stage of development are being constantly updated and improved, which explains why many concepts about principles of their

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implementation are not completely clear.[3] In general terms, nanotechnology manipulates matter at the atomic, molecular or macromolecular levels to create and control objects at nm scale, with the goal of fabricating novel materials, devices and systems that have new properties and functions because of their small size.[4]

The properties of matter undergo a sea change at nanoscale due to diminished gravitational forces and dominant electromagnetic forces. At nanoscale, the laws of quantum mechanics[5] are applied. Increased surface-to-volume ratio, as compared to bulk material, results in unique properties. At this level, properties like colour, strength, surface-to-volume ratio and chemical reactivity start changing leading to new scientific opportunities in developing novel products and applications.

Historically speaking, the famous lecture by R. Feynman, 'There is Plenty of Room at the Bottom', delivered in 1959 at the session of American Physical Society laid down the foundation of the possible creation of nano-sized products by using atoms as their building blocks. The term 'nanotechnology' was coined by Norio Taniguchi in Tokyo in 1974 during the international conference on production engineering. In 1986, K. Eric Drexler propounded the feasibility of creating nanomachines in his famous book, *Engines of Creation: The Coming Era of Nanotechnology*.[6]

Nanotechnology is not a recent phenomenon as perceived commonly. Historical evidence suggests that nanomaterials were in use in various forms, without any scientific theory attached to it. The nano production techniques were passed from one generation to the other for specific applications. People in ancient Egypt used black hair dye made up of lime, lead oxide and a small portion of water. In the course of the dyeing process, nanoparticles of galenite (lead sulfide) were formed[7] which ensured even and steady dyeing. The British Museum showcases 'Lycurgus Cup', a glass bowl made by glass makers of ancient Rome, which has the unusual property of scattering different colours with change of location of light source. Scientists discovered that the glass used in the bowl contains particles of gold and silver in the range of 50–100 nm size. Multicoloured stained glass windows in European churches are another example of the use of gold and other nanoparticles of metals as additives leading to unusual properties.

Nanotechnology holds great promise for defence applications, given its cross-discipline domain. The armed forces are likely to get direct benefit of nanotechnology-enabled applications in the fields of weapon technology, electronics and communication, mobility, stealth, smart uniforms, and adaptive structures. The impact of these technologies will be felt in battlespace systems like geo intelligence, situational awareness, information processing, and intelligence. The applications concerning health monitoring, targeted drug delivery and smart implants will leverage existing war-fighting capabilities. Research in the field involving novel materials will give rise to vehicles that are lightweight and have better armoured protection, better fuel economy, adaptive structure, nuclear, biological and chemical (NBC) protection, and a host of other advantages.

What Makes Nanoparticle Properties So Alluring?

The properties exhibited by materials in bulk often start changing dramatically when reduced to nanoscales. Nanocomposites made up of particle size smaller than 100 nm show exceptional strength. Metals with so-called grain size of around 10 nm are as much as seven times harder and tougher than their ordinary counterparts with grain sizes of hundreds of nm.[8] The exceptional properties of nanomaterials are direct consequence of quantum effect.[9] Due to this effect, the characteristics defining optical, magnetic and electrical properties also undergo sea change. Once nanoscales are achieved, a conducting material in bulk form may start showing semiconductor or insulator properties. Change in colour or appearance at nanoscales is another example of the quantum effect. Gold, as we see, is notably yellow, but once shrunk to nanoscales (10–100 nm) it becomes red if it is spherical or colourless if it is shaped in a ring.[10]

Increased surface-to-volume ratio at nanoscales, compared to bulk material, gives rise to entirely new set of physical properties having an impact on the melting and boiling points, chemical reactivity, and strength. Reactions that occur at the material surface are particularly affected, such as catalysis reactions, detection reactions, and reactions that require the physical absorption of certain species at the material's surface to initiate.[11] Small dimensions thus give rise to unique applications where high speed and high functional density are required. Devices can be made portable and lightweight with high strength to withstand wear and tear. Electronic circuitry can be made to function much faster and more efficiently, along with increased functional integration.

Novel materials with new properties can be created for high-capacity absorption, improved catalytic effect, exceptional mechanical strength, improved sensitivity for sensors, high signal-to-noise ratio, superconductivity, and high-density memory.[12] Although it would appear that the products/applications based on nanotechnology are simple miniaturizations of larger objects, such products based on nanomaterials require a different production approach. The two most common approaches are: 'bottom-up' and 'top-down'. In the bottom-up approach, the fabrication of nanomaterial is done by assembling the individual atoms and then moving up to create larger parts. This is often referred to as self-assembly. The concept of self-assembly already exists in natural biological processes in which molecules self-assemble to create complex structures with nanoscale precision.[13] By the process of self-assembly, nanomaterials having specific functions can be created. The top-down approach entails downsizing and miniaturization. This approach requires precision engineering at nanoscales involving lithographic patterning, embossing or imprint techniques with subsequent etching and coating.[14]

It is perceived that manufacturing by moving individual atoms for the purpose of mass industrial production is not suitable due to the complexities involved; moreover, the time frame required is quite long. Molecular nanotechnology (MNT) is one such process in which nanorobots will be used to create objects and will also be capable of assembling themselves, just like the cells in the organic world.[15] This kind of manufacturing will alter the way industrial processes are being run today. The manufacturing would become cost effective, with negligible waste and high-quality output. However, research in this field is still at a nascent stage and actual product development through molecular manufacturing may be a few decades away.

Current Global Nanotechnology Landscape

Nanotechnology is recognized as a very strong driver for innovation and is therefore seen as a strategic technology for the world's future economy.[16] It is a recognized fact that innovations in science and technology often lead to potential defence applications. Nanotechnology is one such field where basic research can lead to successful innovations, thereby impacting war-fighting strategies. Having recognized its potential as an emerging technology with far-reaching implications and a possible solution to challenges being faced by mankind today, a large number of countries have embarked upon R&D in nanotechnology.

In 2011, Lux Research, an emerging technologies consulting firm, estimated that during the year 2010 the total global nanotechnology funding was approximately US$ 17.8 billion, with corporate R&D

of approximately US$ 9.6 billion.[17] In 2010, Cientifica[18] estimated approximately US$ 10 billion global public investments in R&D per year growing at a rate of 20 per cent, with global investment touching US$ 100 billion by the end of 2014.

United States (US)

The US, being one of the first countries to start a nanotechnology programme in the year 2000, allocated US$ 500 million for setting up the National Nanotechnology Initiative (NNI). From the fiscal year (FY) 2001 through FY 2013, the US has appropriated approximately US$ 17.9 billion for nanotechnology R&D.[19] There were originally eight participating government agencies which have now grown to 27, including the National Aeronautics and Space Administration (NASA), the Department of Defense (DoD), and the Department of Energy (DoE), among others. The thrust of NNI has primarily been the development of fundamental scientific knowledge through basic research.[20] Some of the funding to these agencies is aimed at application development, while others aim at infrastructural technologies.

In order to maintain technological superiority for strategic advantage, the DoD has been the lead agency for investment in military-specific nanotechnologies, with a view to improve the performance of existing systems and also to develop new applications. In the FY 2012, DoD accounted for approximately 23 per cent of total NNI financial outlay.[21] The US Army Research Laboratory, the Air Force Research Laboratory, and the Naval Research Laboratory are playing the lead role in developing defence-related applications alongside the Defence Advance Research Project Agency (DARPA). The US Army has also collaborated with industry and the Massachusetts Institute of Technology (MIT) to establish the Institute for Soldier Nanotechnologies (ISN) to discover and field technologies that dramatically advance soldier protection and survivability capabilities. Five strategic research areas[22] have been identified by ISN to address the broad challenges faced by soldiers. The military R&D in the US is focused at miniature sensors, high-speed processing, unmanned combat aerial vehicles (UCAVs), improved virtual reality training, and enhancement of human performance.[23]

China

Considering the far-reaching implications in entire arena of science and technology, China embarked upon the journey of R&D in nanotechnology as early as 1989 when the atomic force multiplier was created[24] followed by the scanning tunneling microscope, which are key laboratory instruments for nanotechnology research. The R&D was somewhat disjointed without any state sponsor. Over a period of time, patenting activity, publication of research papers and development of standards have become some of the indicators of China's advancements in the field of nanotechnology.

As part of a broad effort to expand basic research capabilities, China identified five areas, including nanotechnology research, that have military applications as major strategic needs or science research plans requiring active government involvement and funding.[25] As a result, the Eighth Five Year Plan (1991–95) listed the research of nanomaterial as one of the government's key projects, prompting the beginning of major investment in nanotechnology.[26] The following years saw coordinated efforts by China for R&D in nanotechnology. Since its Tenth Five Year Plan (2001–05), which earmarked goals for short, medium and long-term development, and Eleventh Five Year Plan (2006–10), China has created an ecosystem in which innovations are driven by academic research and participation by private firms. 'National Mid and Long-term Scientific and Technological Development Plan Guidelines (2006–2020)' were formulated and released which set the road map and targets to be achieved.[27]

Considering the impetus from government, China has become one of the fastest-growing nanotechnology markets in the world, with its value estimated to reach US$145 billion by 2015.[28] Key applications and research areas revolve around nanomaterial for coatings, fabrics, nanofibres, and catalysts. Notable developments have been seen in the transportation industry and in information technology (IT), construction, and health care industries.[29] Other notable areas of research are communication, environmental protection, and agriculture.

The People's Liberation Army (PLA) has also been investing heavily in nanotechnology and appears to understand that this is a key transformational military technology.[30] The Chinese Academy of Science (CAS) is also playing a major role in advancing nanotechnology-based research for military modernization. According to Major General Sun Bailin of the Academy of Military Science, 'nanotechnology weapons could bring about fundamental changes in many aspects of future military affairs and nanotechnology will certainly become a crucial military technology in 21st century.'[31] A 2006 Chinese article lists seven military-related applications for nanotechnology, including potential nanodiscs with a 'million times' the storage of current computers, nanostructures '100 times stronger than steel', the ability to make generic weapons, super thin stealth radar-absorbing coatings, microweapons, nanosattelites, and soldier equipments such as armour, cloth and laser-protected headgear.[32] These findings, correlated with research papers of Chinese origin available on nanotechnology in public domain, indicate that a discourse does exist in China for development of nanotechnology-enabled military applications.

Russia

The major initiative by Russian government for nanotechnology, led by President Vladimir Putin, took off in April 2007. A comprehensive strategy to create a world-class nanotechnology industry resulted in allocation of considerable public resources and by 2009 Russia had become the world's second-largest public spender on nanotechnology.[33] At the face of it, the nanotechnology programme is aimed at economic upheaving; however, government officials have identified defence and national security as priority targets of their nanotechnology projects.[34] In the last decade, Russian political leadership and military leaders discussing sixth-generation warfare[35] referred to the new generation of bio, nano and information breakthrough technologies that will influence warfare by 2020.[36] President Vladimir Putin also underlined the role of nanotechnology that could lead to revolutionary changes in weapons and defence.[37]

Russia adopted the Federal Targeted Programme (FTP) for the development of a nanotechnology industry infrastructure in August 2007. The aim of this programme was the creation of a modern national nanotechnology network infrastructure for the development and realization of the potential of the Russian nanotechnology industry. Several federal agencies, including atomic energy, industry, space, and education were made part of this programme. The developmental programme was allocated a budget of over 100 billion Rubles (US$ 3.3 billion), of which two-thirds was assigned to R&D. In July 2007, Rusnano, a state-owned corporation was created to act as a primary organization to implement the state policy in respect of nanotechnology. Rusnano is involved in multifarious activities such as future projection and road mapping, infrastructure development, R&D, educational projects and awareness, certification and standardization, and international cooperation.

Russian involvement in developing nanotechnology-enabled military applications is noteworthy in the field of rocket propellant fuel, military uniforms[38], nanomaterial, and nanocoatings for MiG and Sukhoi aircrafts.

Japan

In Japan, nanotechnology is considered to be a priority area and financial support is provided by the Ministry of Economic Trade and Industries (METI) and the Ministry of Education, Culture, Sports Science and Technology (MEXT). In 2001, the Second Science and Technology Basic Plan (STBP) laid down the initial goals for research in nanotechnology.[39] Later, Japan categorized nanotechnology as one of its four priority research areas in the next STBP (2006–10).[40] R&D in Japan is focused towards development of novel nanomaterials having applications in the semi-conductor industry, life sciences, and for safe energy generation. There is also considerable funding from private sector aimed mostly at developing applications related to nanoelectronics, nanocoatings, nanofabrication, health care, and biotechnology.

Although, there is no direct evidence to suggest the development of military applications based on nanotechnology in Japan, however, the 'National Defence Program Guideline for FY 2014 and Beyond', which has set up the new guidelines for Japan's national defence, has highlighted the fact that military strategy and military balance will be significantly affected by the progress and proliferation of newer technologies, including nanotechnology.[41]

European Union (EU)

The first reported endeavour of the EU towards addressing the issue of nanotechnology can be traced to 1996.[42] Later in 2002, through the Sixth Framework Programme (FP6) for research and innovation, nanotechnology was recognized as one of the seven thematic priorities with an indicative budget of Euro 1,300 million for nanotechnology alone. In 2005, the EU adopted an action plan called, 'Nanoscience and Nanotechnology: An Action Plan for Europe (2005–2009)', with an objective to define a series of articulated and interconnected actions for the immediate implementation of a safe, integrated and responsible strategy for nanoscience and nanotechnology.[43] Following FP6, the Seventh Framework Programme (2007–13) was unleashed, with special emphasis on research in nanoscience, nanotechnology, materials and new production techniques, with a financial outlay of Euro 3,475 million. The FP7 was later superseded by Horizon 2020,[44] which will run over a period of seven years. The new regime promises to address a widely perceived shortfall in technology transfer and put Europe in a strong position to grasp new opportunities in the commercialization of emerging nanotechnologies across a vast array of different sectors.[45] One of the important aspects of Horizon 2020 programme is Euro 1 billion funding for graphene[46]-related research, which is considered to be the wonder material of the twenty-first century with wide-ranging applications in electronics, energy, automobile, transport, and medicine.

Defence-related funding and research in the EU involves a number of countries, for example, the United Kingdom (UK), Sweden and France. The research areas include nanosensors, electronic devices, nanomaterials, protection against NBC hazards, electronic warfare, and nanotechnology solutions for soldiers.

India

The potential of nanotechnology was realized by the Government of India as early as 2001 when the Nanoscience and Technology Initiative (NSTI) was launched as a mission mode programme in the Tenth Five Year Plan (2002–07) with a budget of approximately Rs 60 million.[47] The Government of India appointed the Department of Science and Technology (DST) as the nodal agency to carry forward the plan. The NSTI was followed by Nano Mission in May 2007, under the Eleventh Plan (2007–12), with a budget allocation of Rs 10 billion.[48] Nano Mission is an umbrella programme for capacity building which envisages the overall development of the field of research in the country so as to tap some of its applied potential for nation's development.[49] The Nano Mission programme has various objectives.[50]

The Nano Mission programme is steered by Nano Mission Council at the apex level, whereas technical programmes are guided by two advisory groups—the Nano Science Advisor Group (NSAG) and the Nano Applications and Technical Advisory Group (NATAG). Significant contribution is being made by other government departments, including the Defence Research and Development Organisation (DRDO), to harness the potential of nanotechnology. The DRDO is currently pursuing R&D in nanotechnology in 30 of its laboratories for defence applications.

While inaugurating a one-day workshop on 'Nanotechnology for Defence Applications',[51] former Defence Minister A.K. Antony stated: 'Nanotechnology is an emerging field, which can lead to the development of new weapon systems and products that can benefit our nation.' This statement underlines the impetus nanotechnology R&D has gathered at the highest echelons of the government. The DRDO is working on areas like sensors, high-energy applications, stealth and camouflage, NBC attack protection devices, structural applications, nanoelectronics, and characterization.[52] The DRDO is also setting up nanomaterial research and production facilities in Hyderabad, Delhi and Kanpur, at a total cost of Rs 10 billion.[53]

India has also entered into bilateral nanotechnology programmes with the EU, Germany, Italy, Taiwan and the US.[54] Other than government and public agencies, private industry has also started working on nanotechnology-enabled commercial products. Two large Indian companies—Reliance Industries and Tata Chemicals—have set up nanotechnology R&D centres in Pune.[55]

Pakistan

The nanotechnology initiative in Pakistan started in 2003 by way of National Commission on Nanoscience and Technology (NCNST), established by the government for an initial period of three years with an investment of US$ 11 million. The mandate for the commission was to promote R&D activities, manpower training and development of infrastructure. After an extension of another two years, the functioning of the commission was suspended in 2008 due to change of government policies.[56] Not to be left behind in the race of developing nanotechnology applications, an elaborate plan has again been set in motion by the Pakistan government in December 2013, with a total funding of approximately US$ 25 million.[57] Interestingly, setting up of laboratories for defence applications has been categorized as one of the key objectives of this initiative, with special emphasis on R&D in aerospace and protective personal clothing. In a latest move, the Pakistan Foundation for Nanotechnology is proposed to be established and this body will formulate five and 10 year plans for nanotechnology.[58]

South Korea

Among the Asian Tigers, South Korea is the leading country in nanotechnology R&D. The Korean National Nanotechnology Initiative was started in December 2000 by the National Science and Technology Council (NTSC).[59] Phase I (2001–05) succeeded Phase II (2006–15), which envisaged securing technological competitiveness to join firmly the global top three nanotechnology nations by 2015.[60] A total investment of approximately US$ 4.85 billion was planned for R&D for the period 2005–15.[61]

Korea has three frontier research programmes[62] and five national nanotechnology fabrication facilities. These are large-scale government R&D programmes for developing nano-enabled applications.

Elsewhere in the World

Nanotechnology R&D is not restricted to above-mentioned countries. Currently, more than 60 countries are pursuing R&D in nanotechnology. Notable progress has been made in nanotechnology R&D by Australia, UK, France, Hong Kong, Singapore, Israel and Iran. Thailand leads the Association of Southeast Asian Nations (ASEAN) countries as it set up it's the National Nanotechnology Centre (NANOTECH) in August 2003 with an annual budget of US$ 11 million. The Thai government recently passed the National Nanotechnology Policy Framework (2012–21), which provides national guidelines for nanotechnology development and calls for science, technology and innovation in nanotechnology to be increased by tenfold.[63] Taiwan was ranked at number four in 2012 in nanotechnology patent holders in the world[64] with an approximate funding of US$ 634 million[65] over 2003–08.

Although the current R&D efforts in most of the countries are directed towards basic research, it is anticipated that as the technology starts maturing, new horizons in civil and military applications will open up.

Nanotechnology-Enabled Military Applications: Soldier in Focus

While nanotechnology is evolving fast, leading to new innovations and product development across various disciplines of science and technology, its profound effect on defence-related applications has long been realized by countries all over the world. Leading economies are investing substantial amount of funds in developing cutting-edge research for exploring military-related, nanotechnology-enabled applications. Nanotechnology has the potential to influence warfare technology in large number of ways. Lighter, stronger, heat-resistant nanomaterials could be used in producing all kinds of weapons, making military transportation faster, strengthening armour, and saving energy.[66] As far as the specific use for the soldier on the ground is concerned, the military use of nanotechnology will lead to higher protection, more lethality, longer endurance, and better self-supporting capabilities.[67]

In a human-centric system of future battlefields, there is a requirement of not only providing better protection to the soldier from bullet or splinter injury, it is imperative that the system should, at the same time, be able to provide better survivability, mobility, execution of group tactics, communication and intelligence, NBC sensing and protection, sensing and reporting of vital body parameters, targeted drug delivery in case of injury, lightweight and smart weaponry, and long-endurance power source; and yet, the entire system should be lightweight and wearable. In this section, nanotechnology-enabled innovations which can be conceived for a soldier have been discussed.

Battle Suit

The requirement of lightweight, flexible anti-ballistic textile, chemical and biological protection, self-decontamination, and switchable camouflage pattern together with thermal control is largely met by nanofibres and nanocomposite-based textile. Nanocomposites consist of a matrix material, usually a polymer with a dispersion of nanoparticles/fibres.[68] These composites provide enhanced thermal, mechanical and electrical properties.[69] Chinese and American researchers have demonstrated a carbon nanotube (CNT)-coated smart yarn, which can conduct electricity and be woven into textile to detect blood or monitor health.[70] It can find its practical utility in the battlefield: when a wounded soldier is not able to send message for medical assistance, the smart clothing will detect the presence of albumin and send a distress signal through radio communication device.

Bullet or splinter injuries during active operations are a dominant factor resulting in military casualties. Extremities are most vulnerable to such injuries. Therefore, body armour that is able to provide complete protection against bullet or splinter injury, yet is flexible, is desirable. While currently used bulletproof jackets and vests do provide protection from medium and low-energy small arms, there is a requirement for protection against more lethal ammunition and multiple strikes without compromising on manoeuvrability and operational effectiveness. The idea is to create a material having similar or superior ballistic properties, with more flexibility and less thickness as compared to currently used Kevlar[71] fabric and its various forms.

Nanotechnology application in shear thickening fluid (STF) has made it possible to create flexible armour. Kevlar has been used for some time now for its anti-ballistic properties, with limited capabilities. However, Kevlar soaked with STF provides much enhanced anti-ballistic properties as compared to Kevlar alone. The STF consists of nanoparticles-filled binders which remain flexible when low shear rate is applied and harden under high shear rate impact in less than a millisecond. Once the stress is removed, it regains its flexible nature. This technology appears to allow conventional ballistic fabric to increase the level and quality of protection it provides without compromising on weight, comfort and flexibility.[72]

It has also been researched and established that incorporating spherical nanoparticles of silicon or titanium dioxide or CNTs in a plastic epoxy matrix offers improved anti-ballistic resistance, together with greatly improved flexibility.[73] The anti-ballistic performance in terms of absorbed energy is more than double so that four layers of Kevlar impregnated with STF can absorb as much energy as absorbed by 10 layers without STF.[74] Another application of nanotechnology which has caught the attention of researchers is the use of magnet-rheological (MR) or magnet-restrictive fluid. The flexible medium filled with nanoparticles becomes rigid when it gets activated electrically. The MR fluids are made up of nanoparticles of iron in a thick or syrup suspension.[75] Once the magnetic field is applied, the fluid becomes thick providing necessary protection against sudden stress or shear caused by bullet strike.

Due to its high-yield strain and high-elastic modulus, CNT is considered to be the material of choice for bulletproof vests. CNTs can be used in number of ways to enhance the performance of the armour. One approach is to increase the hardness by incorporating CNTs in the polymer matrix compound (PMC)-based armour. Single-wall CNT (SWCNT) or multi-wall CNT (MWCNT), or both, can be used for enhanced ballistic properties.[76] CNTs can also be used as reinforcing material for ceramics used for hard body armour, for example, alumina and silicon carbide.[77]

Macroscopic CNT-based fibre shows a unique combination of extraordinary mechanical, thermal and electrical properties, with significant promise for futuristic applications such as next-generation body armour.[78] The CNT-based neat or composite fibres are candidates for the strongest, toughest and stiffest super fibres of the future and exhibit enormous energy absorption capacity at sonic velocity.[79]

Biological and Chemical Protection

Exposure of soldiers to hazardous conditions such as chemicals, gases or biological agents can lead to high battle casualties. Conventional protection suites that are currently in use are heavy, bulky and uncomfortable. Electrospun nanofibres offer properties to act as membrane material for sensing, decomposition and filtration of harmful toxins owing to their lightweight, high surface area and porous nature. The high sensitivity of nanofibres towards chemical or biological warfare agents makes them excellent candidate as sensing surfaces.[80] Metal nanoparticles (silver [Ag], magnesium oxide [MgO], nickel [Ni], titanium [Ti]), which have proven capability in decomposing warfare agents, can also be embedded in nanofibres for enhanced decontamination, thereby providing operational advantage to soldiers.[81]

Health Monitoring and Sensing

For a commander in operations, it is essential to monitor the physical and mental condition of troops for better employability and mission accomplishment. On-body nano health sensors can provide vital body parameters through communication link to the medics assisting the commander. The nano–bio fusion can give rise to unprecedented applications in health treatment. Targeted drug delivery, regenerative medicine and smart implants are some of the most researched areas.[82] Bionanosensors[83] incorporated in clothing, helmet, boots, and gloves can convey information on encountering any health hazard. The US agency DARPA has proposed a system of pumping small nanosensors into the human body to monitor stress levels, disease, inflammation, requirement of nutrition, etc., to feed the medic real-time information.[84] On sensing injury or failure of vital organs, targeted drug delivery can be actuated by bioreaction or by external mechanism.

Another application which can find its widespread use is a transdermal patch (TDP). It is an adhesive tape which can penetrate skin to deliver nano-formulated drugs to the patient.[85] MIT has developed a spray-on biological nanoscale coating using thrombin and tannic acid to stop bleeding. The spray has a very long shelf life and can be carried by soldiers to stop any kind of bleeding.[86] In-situ tissue repair is another promising area of nanotechnology application which can be extended to the battlefield. Electrospun nanofibrous scaffolds have been created to improve wound healing and skin restoration.[87] Other approaches involve bioactive (DNA-carrying) particles that induce specific cell growth and molecular nanomotors to synthesis drugs and releasing drug in a cell.[88]

Tagging and Tracking

Nanoelectronics-enabled small information and communication technology (ICT) devices such as cell phones and smart phones will help in ensuring safe and secure communication in the network-centric warfare scenario. Radio frequencies identification (RFID) can be used to identify enemy from own troops. Nanotechnology alloy-based war tags with RFID and nanosensors can replace the conventional metallic plate identification. The RFID tag can store the complete information of the soldier. The RFID tags could be active or passive with incorporated sensor function for positioning and identification on long distances by using radar reflection characteristics. These RFID tags will also be helpful during rescue and search operations. Once the signal emitted by the sensor is picked up by a receiver, it would be possible to exactly locate the missing soldier. Garments and shoes can be designed around ultra-high frequency RFID tags for access control and positioning.

Communication

Nanotechnology can greatly enhance the communication capability of the soldier. Use of nanotechnology leads to enhanced functionality, improved stability, reduced weight and system miniaturization.[89] Advance chip design using nanomaterials can decrease the size of the device further. Recent advances in nanoelectromechanical systems (NEMS) have led to the development of nanoscale resonators which are used for gigahertz (GHz) signal-processing applications characterized by high data rate up to several gigabits per second (Gbps).[90] A soldier using these devices is thus able to stream live videos of his area of operation for better situational awareness and decision-making.

A team of researchers at Monash University have modelled the world's first 'surface plasma amplification by simulated emission of radiations' (SPASER) using graphene and nanotubes. This could mean that communication devices can become small, efficient and flexible, and can be printed on textile/clothing.[91] Researchers from Nokia have collaborated with Cambridge University to produce the morph phone. This device utilizes nanotechnology to allow bending, rolling and folding.[92] The morph phone will provide to the soldier the ease of portability and communication. Development of gold nanomesh electrodes by researchers at Harvard University has led to its application in fully foldable mobile phone or flat screen display units which can be folded and carried in pockets.[93] Such designs not only reduce the weight of the device and, at the same time, have very low power consumption.

Nanopower

The energy requirement for nano-enabled systems used by future soldiers will grow manifold due to integrated nanosensors, communication devices, smart weapons, biomedicine actuators, adaptive camouflage, ventilation and healing systems, and hosts of other devices. The sources of energy supply have to be low in weight, compact and portable. Therefore, miniaturization of power sources is of foremost importance.

The energy density of a standard lithium-ion battery is good, but its life is limited due to finite charge cycles. However, the development of a nano-structured anode using lithium–vanadium oxide has demonstrated a ten-fold increase in energy density with significant drop in weight.[94] Researchers at Rice University, Houston, have demonstrated an energy storage device based on nanowire array.[95] In this device, all essential elements of the storage device have been integrated in a single nanowire. In another demonstration of a flexible energy storage device, researchers at Stanford University have found a cheap and efficient method of manufacturing a lightweight, paper-based battery and super capacitor using fabric soaked in a special ink fused with nanoparticles.[96] This device leads to the printed textile having an energy storage property. Other advances in miniaturization of energy storage devices include peizoelectric nanogenerator, self-powered nanodevice and triboelectric nanogenerator. Other methods of generating energy for nanodevices are nanowire solar cells[97], organ dye-sensitized solar cell with nanowires[98], quantum dot solar cells[99], and fullerene/CNT solar cells.[100] These devices reduced to the nano-scale can be integrated with the uniform worn by the soldier, on the helmet or weapon, or carried on body.

Smart Helmet

One of the most essential part of soldier's combat gear is the helmet. Conventional helmets are made up of synthetic fibre, Kevlar and aramid, which offer improved protection against small arm fire and blast shock waves. Some present-day helmets also incorporate provisions to integrate night vision devices and cameras. The efforts of researchers have been to reduce the weight of the helmet and, at the same time, to improve ballistic performance. Owing to high strength, lightweight and good absorption capabilities of CNTs, polymatrix nanocomposites, where a polymer matrix is reinforced by nanoparticles like CNTs, will be the material of choice for headgear in the future.[101] By using highly ordered CNT arrays, field emission visor display can be created to provide high-resolution display along with wide-angle (180 degree) display. The display will also have real-time simulation awareness and night vision capabilities. Biometric facial recognition capability to recognize enemy or friend will also be incorporated using three-dimensional (3-D) scene segmentation technology and two-dimensional (2-D) database comparator.[102] By using STF, the helmet can be categorized as a platform system equipped with multi-sensors to undertake various tasks of surveillance, positioning and identification, radio frequency and audio communication, biological and chemical sensing, sniper detection, and life sign monitor using nanosensors and nanoelectronics.[103]

Adaptive Camouflage

Camouflage and concealment is a tactical manoeuvre to minimize the possibility of detection. Conventional methods of camouflage involve use of disruptive clothing, nets, paints, etc., to merge with the background terrain. However, conventional techniques are specific to a particular terrain and surroundings.

Adaptive camouflage is a concept wherein the material surface changes its external appearance in response to preprogrammed stimulus in the environment in which it operates.[104] Nanotechnology-based techniques under development are categorized into active and passive systems. In an active system, nanotechnology-based fibre coating, light-emitting diodes (LED), optical sensors, and power source are used. On receiving the signal from the optical sensor, the fibre will change colour as per the surroundings. The passive system uses tunable photonic crystals. Researchers at University of California have succeeded in changing the colour of nano-sized particles of iron oxide by applying an external magnetic field.[105] These photonic crystals are fully tunable in the visible range of spectrum.[106] Complete nanotube-based photodetector architecture can operate at very high speed in real time to adapt to the surroundings. Nanotube interconnections, switches, sensors and emitters can make the whole design compact with very low power consumption.[107]

Soldier as a System: System of Systems

The basic idea behind proposing a concept of nanotechnology-enabled application for soldier as a system is to enhance the combat capability of a soldier, while, at the same time, equip him to protect and defend himself in adverse situations. It is an established fact that in future warfare, man–machine interface is likely to become more complicated with advances in technology; however, the individual soldier will remain central to the entire spectrum of warfare.

Soldier as a system is, in fact, a 'system of systems', in which nanotechnology-enabled applications are proposed to be integrated in order to provide a multidimensional capability to the soldier. There are five broad areas where these applications can be categorized as subsystems and integrated to form one major system.

1. combat suit;
2. smart helmet;
3. biosensor and drug delivery network;
4. communication; and
5. weapons.

The future combat suit will be capable of providing protection against small arms threat and splinter injuries by integrating the bulletproof jacket as an integral part. The combat suit is nanomaterial enabled, providing protection against biological and chemical agents. A network of nanosensors can also be interwoven to monitor physical and mental well-being of the soldier. Use of single or multi-walled CNTs will help in thermal management by providing ventilation, cooling and insulation as per external environmental conditions. The RFID textile antennas embedded in the combat suit will help in identifying the foe or friend. In case of close combat operations or operations in urban areas, RFID tagging will help the fellow soldiers to identify a fellow soldier in the area of operation. The RFID tagging will also help in access control, accurate positioning of own troops and their movement. Use of nanofibres for adaptive camouflage for the combat suit will provide concealment from getting detected by the adversary. Adaptive camouflage will also be useful in employing the troops in all types of terrains without going into the time-consuming process of applying a new scheme of camouflage pattern to weapons, uniform and equipment.

The smart helmet will not only provide protection from bullet or splinter injuries but also act as a platform for information gathering, processing and sharing. Nanofibre and nanocomposite-based helmet shell will be lightweight and have higher impact resistance compared to conventionally used helmets. Use of STF in helmet fabrication will provide head size flexibility and comfort in wearing the helmet with ventilation and thermal management. Reduction in overall weight will lead to incorporation of other nano-enabled devices which can be mounted on the helmet. The core value of nanotechnology lies in miniaturization of the mounted camera, array antenna and sensors. Owing to the small overall weight of the shell of the helmet, nanodevices and multi-sensor array can be mounted on the helmet. The visor will act as an organic light-emitting diode (OLED) display unit acting in tandem with optical and infrared camera. Use of acoustic array technology will help the soldier in identifying the location from where the gunshot is fired during combat. An electroencephalogram (EEG) and heart rate sensor will be embedded in the helmet due to nano size for monitoring these vital signals. The visor display and vital body signs can also be communicated to the commander in the rear for live situational awareness.

Biosensors and targeted drug delivery will be the hallmark of innovations in the field of nanotechnology. Commanders in the rear will never lose touch with each soldier under their command during operations, be it their physical or mental state. Sub-skin biosensors will help the medics in the rear to monitor and provide onsite medical assistance in case of any bullet injury or emergency. Speedy recovery or evacuation will bring down the causality rate.

Communication is one area where large opportunities exist for improving the communication capabilities of a soldier. Primarily, nanotechnology will help in building up extremely small size, rugged, flexible and low on power consumption communication devices. However, there may be a requirement of working out completely new protocols for voice and data transmission. Data rate will be enhanced multifold, which will be the key ingredient of fast decision cycle. A platoon or company commander will be able to monitor and view the immediate battlespace through the digital eyes and ears of his troops.

One of the most potential innovations for nanotechnology will be in the field of weapons. Using nanomaterials for weapons will lead to lightweight and rugged weapons and firing mechanisms. Nanotechnology-enabled weapons will incorporate micro radar for target tracking and feedback by the projectile. Once the projectile leaves the barrel, the sensor on the projectile gets activated and homes on to the target. These projectiles will carry camera, radar array, sensors and explosives onboard, enabled through nanotechnology. In advance innovations, the path correction of the projectile while in flight will also be possible, even for small arms ammunition. Remote operation of small arms via radio frequency link is also close to reality.

Impact of Nanotechnology on Land Warfare

The development and use of nanotechnology-enabled weapons and systems will bring in changes in generic capabilities of defence forces. More specifically, land forces will find significant impact on engagement capability by way of lighter, precise and long-endurance weapons and systems. Use of nanocomposites, nanofibres and CNTs will bring down the weight of the equipment carried by the soldier. Miniaturization of sensors, power sources and communication equipment will help him in sustaining long-drawn operations and, at the same time, health monitoring systems, remote bio-informatics and situational awareness will leverage his fighting capabilities.

Use of lighter and stronger bulletproof jacket, helmet, body suit, adaptive camouflage, reduction in electromagnetic signature, and nanoscale biosensors will greatly enhance the protection level of land forces. Navigational aids enabled through NEMS, quantum dots and CNTs will enhance manoeuvring and navigational capability of land forces. In the era of information-dominant battlespace, functional capability of land forces will be enhanced through collection of real-time information and its presentation in usable form for decision-making. Nanotechnology-inspired encryption and compression of data will also have significant impact on the decision-making cycle.

Conclusion

Advances in nanotechnology over the last 10–15 years have resulted in discovery of a new phenomenon—radical properties of material and their functions at nanoscale. Incorporation of these newly discovered properties in existing technologies has led to innovations not only in products existing in commercial domain but also in defence-related applications. History shows that today's scientific realities can readily become tomorrow's realities, and today's scientific explorations can become sources of development for tomorrow's socially productive forces and military combat powers.[108] It is in this context that nanotechnology, which is going through a phase of intense research and evolution, is likely to deliver unprecedented applications like micro sensors, soldier's protective clothing, targeted drug delivery systems, communication and intelligence devices, nanopower sources, and navigational and surveillance aids. These applications are not only going to ease the carried load of dismounted soldier but afford better engagement capability, survivability, endurance, protection, stealth, and decision-making as well.

The efforts made by Government of India in establishing 180 centres of excellence (COEs) in various parts of the country, together with the efforts being made by DRDO-led R&D, have created an ecosystem for fruitful applications. Notable progress has been made in the fields of nanostructures, microelectromechanical systems (MEMS) and NEMS, advance sensors, energy applications, stealth and camouflage, NBC devices, and characterization. A number of patents have been registered by Indian scientists to consolidate their R&D efforts. It is desirable that private industries working in this field also collaborate with government agencies and integrate their efforts to develop applications best suited for the Indian defence scenario. Not only in soldier-centric applications, the Indian defence space will benefit from such research and innovation in almost all dimensions. Ubiquitous sensor network deploying autonomous and unattended sensors along the border will help in real-time surveillance. Lightweight nanocomposites with improved armour protection will provide better fuel economy, long endurance, more weapon-carrying capability, and lethality. Unmanned aerial vehicles (UAVs) and UCAVs can be further miniaturized and employed at platoon or section level to have 'hover-and-stare' capability for close combat operations, operations in build-up areas and in difficult terrain.

Countries which have started early in initiating nanotechnology-related R&D are bound to get rich dividends. It is contemplated that sufficient advances made in molecular manufacturing will give distinct edge to the country engaged in its development to disarm its adversary without any physical engagement. Although convergence of biotechnology with nanotechnology is likely to provide greater safety and immunity, however, the possibility of hostile application in creating genetically engineered pathogens specific to particular genotype or ethnic background cannot be ruled out. These pathogens may remain dormant for a very long time and become active only on meeting certain conditions or remote actuation. Therefore, there exists a requirement of balancing the whole act of R&D and development of applications to new vulnerabilities to which humans and environment are likely to get exposed.

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