Nanotechnology and preventive arms control

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Executive Summary

Nanotechnology (NT) is about analysis and engineering of structures with size between 0.1 and 100 nanometres (1 nm = 10^{-9} m). At this scale, new effects occur and the boundaries between physics, chemistry and biology vanish. NT is predicted to lead to stronger but lighter materials, markedly smaller computers with immensely increased power, large and small autonomous robots, tools for manipulation of single molecules, targeted intervention within cells, connections between electronics and neurones, and more.

In recent years military research and development (R&D) of NT has been expanded markedly, with the USA far in the lead. US work spans the full range from electronics via materials to biology. While much of this is still at the fundamental level, efforts are being made to bring applications to the armed forces soon. One quarter to one third of the Federal funding for NT goes to military R&D, and the USA outspends the rest of the world by a factor 4 to 10.

NT applications will likely pervade all areas of the military. Very small electronics and computers will be used everywhere, e.g. in glasses, uniforms, munitions. Large-scale battle-management and strategy-planning systems will apply human-like reasoning at increasing levels of autonomy, integrating sensors, communication devices and displays into an ubiquitous network. Stronger but light-weight materials, more efficient energy storage and propulsion will allow faster and more agile vehicles in all media. NT-based materials and explosives can bring faster and more precise projectiles. Small arms, munitions and anti-personnel missiles without any metal can become possible. Systems worn by soldiers could monitor the body status and react to injury. Systems implanted into the body could monitor the biochemistry and release drugs, or make contacts to nerves and the brain to reduce the reaction time, later possibly to communicate complex information. Autonomous land vehicles, ships and aircraft would become possible mainly through strongly increased computing power. By using NT to miniaturise sensors, actuators and propulsion, autonomous systems (robots) could also become very small, principally down to below a millimetre – fully artificial or hybrid on the basis of e.g. insects or rats. Satellites and their launchers could become small and cheap, to be used in swarms for earth surveillance, or for anti-satellite attack. Whereas no marked change is expected concerning nuclear weapons, NT may lead to various new types of chemical and biological weapons that target specific organs or act selectively on a certain genetic or protein pattern. On the other hand, NT will allow cheap sensors for chemical or biological warfare agents as well as materials for decontamination. Most of these applications are ten or more years away.

Using criteria of preventive arms control, potential military NT applications are evaluated. New conventional, chemical and biological weapons would jeopardise existing arms-control treaties. Armed autonomous systems would endanger the law of warfare. Military stability could decrease with small distributed battlefield sensors and in particular with armed autonomous systems. Arms racing and proliferation have to be feared with all applications. Strong dangers to humans would ensue from armed mini-/micro-robots and new chemical/biological weapons used by terrorists. Negative effects on human integrity and human rights could follow indirectly if body manipulation were applied in the military before a thorough societal debate on benefits, risks and regulation.

To contain these risks, preventive limits are recommended in seven areas:

- Distributed sensors below several cm size should be banned.
- Metal-free small arms and munitions should not be developed. The Treaty on Conventional Armed Forces should be kept and updated as new weapons systems would arrive.
- A moratorium of ten years for non-medical body manipulation should be agreed upon.
- Armed autonomous systems should optimally be banned, with limits on unarmed ones; if the former is not achievable, at least for the decision on weapon release a human should remain in the loop.
- Mobile systems below 0.2 - 0.5 m size should be banned in general, with very few exceptions.
- A general ban on space weapons should be concluded.
- The Chemical and Biological Weapons Conventions should be upheld and strengthened.

As the leader in military NT R&D, the USA has a crucial role concerning proliferation as well as arms control. Since the most dangerous military NT applications in the hands of opponent states or terrorists could threaten also the USA, preventive limits should be in its enlightened national interest.

In the long term, preventing misuse of NT and associated powerful technologies will require very intense inspection rights and criminal law also on the international level, calling for strengthening all elements in the international system that move in this direction.

Zusammenfassung

Die Nanotechnologie (NT) befasst sich mit der Untersuchung und Gestaltung von Strukturen, die sich in Größen zwischen 0,1 and 100 Nanometer (1 nm = 10^{-9} m) bewegen. Bei dieser Größenordnung treten neue Effekte auf, und die Grenzen zwischen Physik, Chemie und Biologie verschwinden. Die Experten sagen voraus, dass NT festere und gleichzeitig leichtere Materialien, erheblich kleinere Computer mit unermesslich gesteigerter Leistung, große und kleine autonome Roboter, Werkzeuge für die Handhabung einzelner Moleküle, gezielte Eingriffe in Zellen, Verbindungen zwischen Elektronik und Neuronen und anderes mehr hervorbringen wird.
In den letzten Jahren ist die militärische Forschung und Entwicklung (FuE) im Bereich der NT erheblich ausgeweitet worden. Im weltweiten Vergleich liegen die USA deutlich in Führung. Dort wird die gesamte Bandbreite von Elektronik über Materialien bis hin zur Biologie bearbeitet. Auch wenn vieles davon noch Grundlagenforschung ist, gibt es dort doch heute schon Vorbereitungen, den Streitkräften bald Anwendungsmöglichkeiten zur Verfügung zu stellen. Ein Viertel bis ein Drittel der Regierungsausgaben für NT auf Bundesebene steht für militärische FuE zur Verfügung, und die USA geben 4 bis 10 mal so viel dafür aus wie der Rest der Welt.
NT-Anwendungen werden alle Bereiche des Militärs durchdringen. Hierzu zählt der umfassende Einsatz sehr kleiner Elektronik und Computer, z.B. in Brillen, Uniformen, Munition. Komplexe Schlachtführungs- und Strategieplanungssysteme werden zunehmend autonom funktionieren und menschenähnliche Überlegungen anstellen, wobei sie Sensoren, Kommunikationsgeräte und Anzeigeeinheiten zu einem allgegenwärtigen Netzwerk verbinden. Festere und dabei leichtere Materialien, effizientere Energiespeicher und Antriebe ermöglichen den Bau schnellerer und beweglicherer Land-, Wasser-, Luft- und Raumfahrzeuge. Des weiteren können NT-basierte Materialien und Sprengstoffe zur Herstellung schnellerer und genauerer Geschosse verwendet werden. Denkbar sind metallfreie Kleinwaffen, Munition und Antipersonen-Flugkörper.
Weitere Überlegungen zielen darauf ab, dass von Soldaten getragene Systeme den Körperzustand überwachen und auf Verwundungen reagieren. In den Körper implantierte Systeme sollen in der Lage sein, die Biochemie zu überwachen und Drogen abzugeben oder Kontakte zu Nerven und Gehirn herzustellen, um die Reaktionszeit zu verringern. In einem späteren Stadium sollen so eventuell komplexe Informationen übertragen werden.
Vor allem durch die stark anwachsende Rechnerleistung soll es ermöglicht werden, autonome Landfahrzeuge, Schiffe und Flugzeuge herzustellen. Durch die NT können Sensoren, Aktoren und Antriebe miniaturisiert werden, um kleinste (grundsätzlich bis unter ein Millimeter Größe) autonome Systeme (Roboter) zu bauen – vollständig künstlich oder hybrid auf der Grundlage von z.B. Insekten oder Ratten. Satelliten und ihre Startgeräte könnten klein und billig werden, so dass erstere in Schwärmen für die Erdüberwachung oder für Antisatelliten-Angriffe genutzt werden könnten.
Zwar ist bei Kernwaffen keine große Veränderung zu erwarten, NT kann aber zu verschiedenen neuen Arten von chemischen und biologischen Waffen führen, die auf spezifische Organe zielen oder selektiv auf eine bestimmte Eiweißstruktur oder auf ein genetisches Muster hin aktiv werden. Andererseits wird NT billige Sensoren für chemische oder biologische Waffen sowie Materialien zur Entgiftung zur Verfügung stellen.
Mit den meisten dieser Anwendungen ist erst in einem Zeitraum von zehn oder mehr Jahren zu rechnen.

Mögliche militärische NT-Anwendungen müssen unter den Kriterien der Präventiven Rüstungskontrolle bewertet werden. Neue konventionelle, chemische und biologische Waffen bergen die Gefahr in sich, vorhandene Rüstungskontrollverträge auszuhöhlen. Bewaffnete autonome Systeme stellen das geltende Kriegsvölkerrecht in Frage. Der Einsatz kleiner, verstreuter Gefechtsfeldsensoren und vor allem bewaffneter autonomer Systeme kann die militärische Stabilität verringern. Bei allen Anwendungen sind Wettrüsten und Weiterverbreitung zu befürchten. Bewaffnete Klein-/Kleinstroboter und neue chemische/biologische Waffen stellten eine neuartige Gefahr für die Allgemeinheit dar, wenn diese in die Hände von Terroristen fielen.

Negative Wirkungen auf die menschliche Unversehrtheit und die Menschenrechte wären möglich, wenn Körpermanipulationen beim Militär vor einer gründlichen gesellschaftlichen Debatte über Nutzen, Risiken und Regulierung zum Einsatz kämen.
Um diese Risiken zu begrenzen und zu kontrollieren, werden in sieben Bereichen vorbeugende Begrenzungen empfohlen:

- Verteilte Sensoren unterhalb einiger Zentimeter Größe sollten verboten werden.

- Metallfreie Kleinwaffen und Munition sollten einem Verbot unterliegen. Der Vertrag über Konventionelle Streitkräfte in Europa sollte weiter Bestand haben und mit dem Aufkommen neuer Waffenarten aktualisiert werden.

- Nicht-medizinische Körpermanipulationen sollten einem zehnjährigen Moratorium unterliegen.

- Bewaffnete autonome Systeme sollten möglichst verboten, der Einsatz nicht bewaffneter autonomer Systeme sollte vertraglich geregelten Beschränkungen unterliegen; wo dies nicht erreichbar ist, sollte der Waffeneinsatz menschlicher Entscheidung vorbehalten bleiben.

- Bewegliche Systeme unter 0.2 - 0.5 m Größe sollten mit sehr wenigen Ausnahmen umfassend verboten werden.

- Ein allgemeines Verbot von Weltraumwaffen sollte verabschiedet werden.

- Die Übereinkommen zu chemischen und biologischen Waffen sollten ihre Gültigkeit uneingeschränkt behalten und neuen Entwicklungen angepasst werden.

Aufgrund ihrer Führung in militärischer Forschung und Entwicklung auf dem Feld der Nanotechnologie spielen die USA sowohl bei einer möglichen Verbreitung der Waffentechnologie als auch bei Rüstungskontrollmaßnahmen eine entscheidende Rolle. Weil die gefährlichsten militärischen NT-Anwendungen in den Händen von gegnerischen Staaten oder Terroristen auch die USA gefährden könnten, müssten vorbeugende Beschränkungen in ihrem aufgeklärten nationalen Interesse liegen.
Auf lange Sicht müssen zur Verhinderung des Missbrauchs von NT und ähnlich wirkungsmächtigen Technologien auch im internationalen Bereich sehr weit reichende strafrechtliche Regelungen und umfassende Inspektionsrechte geschaffen werden. Daher müssen alle Elemente im internationalen System gestärkt werden, die in diese Richtung gehen.

1 Introduction

1.1 Nanotechnology: The Next Industrial Revolution

In the coming decades, nanotechnology (NT) is expected to bring about a technological revolution. NT (including nanoscience) deals with structures of sizes between 0.1 nanometre (single atom) and 100 nm (large molecule). 1 nm = 10^{-9} m is a billionth of a metre; for comparison, Table 1.1 gives a few typical sizes.

Table 1.1 Typical sizes for comparison. 1 micrometre (μm) = 10^{-6} m = 1,000 nm; 1 nm = 10^{-9} m; 1 picometre (pm) = 10^{-12} m = 0.001 nm; 1 femtometre (fm) = 10^{-15} m = 0.000,001 nm.

Atomic nucleus	1-7 fm
Silicon atom (in crystal)	0.24 nm
Water molecule (largest diameter)	0.37 nm
Carbon nanotube (diameter)	0.7-3 nm
DNA molecule, width	2 nm
Protein molecule (hemoglobin, diameter)	6 nm
Transistor in modern integrated circuit	100 nm
Animal cell (diameter)	2-20 μm
Human hair (diameter)	50-100 μm

NT is about investigating as well as manipulating matter on the atomic and molecular level.[1] This is an interdisciplinary endeavour. In the analysis of phenomena as well as in the design of systems at the nanoscale, the borders between the different scientific disciplines become blurred – physics, chemistry, biology, medicine, computer science and their respective sub- and intermediate disciplines such as mechanics, electronics, biochemistry, genetics, neurology, artificial intelligence, robotics meet according to the respective object of study. Developments in the various areas will mutually accelerate each other. The concept of converging technologies is gaining ground.[2]

Nanoscale structures can be made top down: as in microelectronics, material is removed or added using macroscale equipment. This gets the more expensive, the smaller the structures become. In particular the lithography process for structuring semiconductor surfaces will run into problems with further miniaturisation. For some systems, copying from master patterns (e.g. by stamping) may help. Alternatively, nanostructures may be

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[1] For a general overview, see e.g. B. Bhushan (ed.): Springer Handbook of Nanotechnology, Berlin etc.: Springer 2004.

[2] M.C. Roco, W.S. Bainbridge (eds.): Converging Technologies for Improving Human Performance – Nanotechnology, Biotechnology, Information Technology, and Cognitive Science. Boston, MA: Kluwer 2003. The workshop of December 2001 had been sponsored by the US National Science Foundation and the Department of Commerce.

produced bottom up where components arrange themselves by physical/chemical forces, as in self-organisation of alcane-thiol molecules adhering to a gold surface. Forming complex, non-periodic structures such as three-dimensional computing/storage elements and their connections, is much more difficult. Nevertheless, economic production will require bottom-up processes – from simple self-assembly to micro- and nano-machinery and life-like growth.

The final goal of NT is the control of the type and three-dimensional position of each single atom in a molecule or a larger structural unit – 'shaping the world atom by atom'.[3] The only limits are set by the fundamental laws of nature. This has been the idea behind 'molecular NT' – the visionary concept of molecular machines, and in particular a universal molecular assembler.[4] The latter would be a program-controlled molecular machine that synthesises arbitrary molecules and larger units by selectively taking existing building blocks from a feedstock or the environment, and mechanically moving them to the intended place with atomic precision where they form the intended bonds (mechanosynthesis). This is somewhat similar to the processes within living cells where information-carrying molecules (DNA) are being read, according to this code protein factories (ribosomes) take specific amino acids from the surrounding fluid and assemble them into proteins. With the appropriate program, the assemblers could self-replicate, with their number growing exponentially. After the required number of generations, assembly of the intended end products would start. Goods production would be very cheap and autonomous, needing human work (in theory) only at the directing level or at the beginning. With such control at the nanoscale would come full understanding of life processes, with the capability to modify and manipulate them – for eradicating illness and ageing, for better organs, for contacting the brain neurones. Molecular assemblers could build extremely small data-storage and -processing structures. With memory sizes and processing speeds increasing by many orders of magnitude, 'genuine' artificial intelligence (AI) would arrive. AI would reach human levels of competence in a few decades and then fast transcend it, advancing technology much faster. Visionary concepts connected to molecular NT include down/uploading personalities into a computer and exploitation of the resources of outer space, including large-scale space colonies.[5]

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3 This is the ambitious wording of a brochure distributed by the US National NT Initiative: Nanotechnology Research Directions: IWGN Workshop Report. Washington DC: National Science and Technology Council Sept. 1999. In: http://www.wtec.org/loyola/nano/IWGN.Research.Directions/IWGN-rd.pdf (10 Sept. 2002).

4 K.E. Drexler: Molecular engineering: An approach to the development of general capabilities for molecular manipulation. In: Proceedings of the National Academy of Sciences 78 (1981) 9, pp. 5275-5278. Ders., Engines of Creation – The Coming Era of Nanotechnology. New York: Anchor/Doubleday 1986/1990.
Proponents as well as sceptics of molecular NT often refer to a famous speech by physicist R. Feynman where he talked about automatic production of extremely small parts by a billion small machines that were produced by successive stages of miniaturisation; mechanical surgeons small enough to enter blood vessels; inspiration by biological systems; synthesis of arbitrary chemical substances (chemical stability permitting) by manoeuvring atom by atom: R. Feynman: There's Plenty of Room at the Bottom: An Invitation to Enter a New Field of Physics. Speech, 29 December 1959, American Physical Society Annual Meeting, California Institute of Technology. In: http://www.its.caltech.edu/~feynman (25 Aug. 2003).

5 E.g. Drexler 1986, loc. cit. (note 4). H. Moravec: Mind Children – The Future of Robot and Human Intelligence. Cambridge MA/London: Harvard University Press 1988. T. McKendree: The logical core architecture. In: Nanotechnology 9 (1998), 3, pp. 212-222. R. Kurzweil: The Age of Spiritual Machines – When Computers Exceed Human Intelligence. New York etc.: Penguin 1999. R.A. Freitas: Nanomedicine, Vol. I: Basic Capabilities. Georgetown TX: Landes Bioscience 1999. C.A. Haberzettl: Nanomedicine: destination or journey? In: Nanotechnology 13 (2002), 4, pp. R9-R13.

Molecular NT could develop into very scary scenarios, not only if used for weapons.[6] Despite its potential importance, molecular NT and related ideas have been practically ignored by the mainstream-science community.[7] Very few articles, not in peer-reviewed scientific journals, refute the concept as impossible or not to be expected for a long time.[8] Sidestepping universal molecular assemblers and self-replicating nano-robots, many of the other molecular-NT-related ideas were presented as realistic possibilities at the US converging-technologies workshop of 2001.[9]

Because it is not obvious that the concepts of molecular NT run counter to the laws of nature or are technologically impossible, they should be taken seriously as principal possibilities. Their discussion is necessarily more speculative.[10]

At the nanoscale, matter exhibits different properties. Geometrically, in smaller particles or pores the surface per mass or volume increases. This effect can greatly improve catalysis, storage density for fuels (e.g. hydrogen) and reaction efficiency and power density of energy conversion (e.g. in fuel-cell membranes). In bulk materials, smaller crystallites can improve mechanical properties. Another effect is quantum-mechanical. In small particles, the electrons are confined to few size-dependent energy levels. The electrical and optical properties can be tuned. With specific coatings, nanoparticles fluorescing at certain colours can be used as biological or medical markers. Carbon nanotubes can be metallic or semiconducting. They could be used for electric interconnects, for memory or switching in future high-density computers. With diameters of a few nm, they promise field emission of electrons (without heating the cathode) in displays. The tensile strength of carbon nanotubes is 100-fold higher than for steel while the density is only 1/6. If

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6 The warnings of the leading computer scientist B. Joy have become widely known: B. Joy: Why the future doesn't need us – Our most powerful 21st-century technologies – robotics, genetic engineering, and nanotech – are threatening to make humans an endangered species, Wired 8.04 (2000). In: http://www.wired.com/wired/archive/8.04/joy_pr.html (16 Jan. 2003). For a discussion of international-security implications of molecular NT see Gubrud M.: Nanotechnology and International Security. In: 5th Foresight Conference on Molecular Nanotechnology. 1997. In: http://www.foresight.org/Conferences/MNT05/Papers/Gubrud (31 Oct. 2000).

7 Whereas there are several articles on details of molecular assemblers in the scientific literature (e.g. R.C. Merkle: A proposed "metabolism" for a hydrocarbon assembler. In: Nanotechnology 8 (1997), 4, pp. 149-162. Ders.: Molecular building blocks and development strategies for molecular nanotechnology. In: Nanotechnology 11 (2000), 2, pp. 89-99. J.S. Hall: Architectural considerations for self-replicating manufacturing systems. In: Nanotechnology 10 (1999), 3, pp. 323-330), I am not aware of any refereed paper criticising the basic concept.

8 There are two articles in Scientific American. One maintains that 'self-replicating, mechanical nanobots are simply not possible in our world' (R.E. Smalley: Of Chemistry, Love and Nanobots. In: Scientific American 285 (2001), 3, pp. 76-77). The other states that such systems would be rather biology-like; others would not arrive in the foreseeable future (G.M. Whitesides: The Once and Future Nanomachine. In: Scientific American 285 (2001), 3, pp. 78-83). Molecular-NT proponents have fast published detailed refutations (K.E. Drexler et al.: On Physics, Fundamentals, and Nanorobots: A Rebuttal to Smalley's Assertion ... In: Foresight Update no. 46 (30 Sept. 2001), pp. 6-7. In: http://www.imm.org/SciAmDebate2/smalley.html (4 Nov. 2003). K.E. Drexler et al.: Many Future Nanomachines: A Rebuttal to Whiteside's Assertion ... In: Foresight Update no. 46 (30 Sept. 2001), pp. 8-17. In: ttp://www.imm.org/SciAmDebate2/whitesides.html (4 Nov. 2003)). A later exchange of opinions did not bring much clarification either: K.E. Drexler/R.E. Smalley: Nanotechnology – Drexler and Smalley make the case for and against "molecular assemblers". In: Chemical & Engineering News 82 (2003), 48, pp. 37-42.

9 These include: full understanding of the human mind and brain, augmenting brain memory, NT-based implants as replacement for human organs, nano-robots for medical intervention in cells, slowing down or reversing ageing, brain-to-brain and brain-to-machine interfaces, robots and intelligent agents that embody aspects of human personality, computer-based social-science prediction of society and advanced corrective actions (Roco/Bainbridge, loc. cit. (note 2)).

10 For reasons of space, molecular NT will be no further discussed here.

longer fibres, ropes and composite materials can be produced, carbon nanotubes would bring much stronger material at reduced weight.

NT comprises very many areas and aspects. They can be subdivided according to the degree of complexity of the structures as in Table 1.2. Table 1.3 gives exemplary production processes of NT.

Table 1.2 Subdivision of NT areas according to degree of complexity (dimensionality increases from point-like to three)

Object class	**Example**
Homogeneous/periodic (bulk)	
Powder of nanoparticles – also in solvent	Paint, sunscreen
Nanotubes, nanowires	Carbon nanotube
Simple layer with nm thickness, e.g. by adsorption of molecules from solution, often in preferential orientation by self organisation; also by fixing of powder by firing	Diamond layer for hard surface, monolayer for molecular electronics, protective coatings, solar-power generation
Three-dimensional layered arrangement	Magnetic storage
Three-dimensional periodic/random arrangement	Protein crystal, zeolite, three-dimensional molecular memory
Complex structure	
Linear chain	Information-carrying molecule (as DNA)
Mostly on a surface, little depth	Scaled-down microelectronics, nano-mechanical device
Produced by surface techniques, but many layers	Vertical-cavity surface-emitting laser
Fully three-dimensional, no self-replication	DNA scaffold, bio-molecular computer, nano-machine
Fully three-dimensional, with self-replication	Self-replicating nano-robot

Table 1.3 Examples of NT production processes

Particles from gas phase (flame, plasma)
Sol-gel process for composites
Optical lithography, electron-/ion-/atom-beam lithography
Stamping, imprinting
Self-assembly
Scanning-probe microscopes: manipulation of individual atoms/molecules on a surface
Mechanosynthesis (molecular NT)

Research and development (R&D) of NT got a strong boost when – prompted by a perceived lag behind Europe and Japan – the USA founded the National NT Initiative (NNI) in late 2000. In the following years, spending by the US and in turn by Japan and Europe was increased repeatedly. In 2003, $ 700-800 million were spent by governments each in the USA, Western Europe, Japan, and the rest of the world.[11] Already in 2001, more than 30 countries had NT activities and plans.[12]

In Germany, total public NT funding was € 153 million in 2001 and about 198 million in 2002.[13] The European Union is spending an annual average of € 175 million.[14]

In addition to the public money, there is significant R&D investment world-wide, by large multi-national corporations as well as NT start-up businesses supported by venture capital.

First NT products (e.g., nano-layered magnetic disk heads, nanostructured catalysts, nanoparticles in cosmetics) have already arrived. Huge market increases are foreseen; one outlook mentioned world-wide sales in 10-15 years of more than $ 1 trillion per year.[15]

Benefits from NT are expected in many areas, among them: stronger but lighter materials, improved solar cells, markedly smaller computers with immensely increased speed and exhibiting general intelligence, micro- and nano-tools, large and small autonomous robots, great progress in molecular biology with the potential for medical intervention within cells, direct connections between electronic devices and nerve cells or the brain.[16]

At the same time, NT can bring large risks. Presently, the most urgent problem stems from nanoparticles and nanofibres.[17] With NT increasingly used throughout society, dangers can arise not only for health and environment. Jobs can be lost, a 'nano divide' can develop, omnipresent sensors can endanger privacy, manipulation of the human body can threaten its integrity.[18]

Given its far-reaching potential, NT can have strong effects on warfare and the armed forces, however, there is not yet much literature on military uses of NT. Most contribu-

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[11] M.C. Roco: Government Nanotechnology Funding: An International Outlook. NSF 2003. In: http://www.nano.gov/intpersp_roco_june30.htm (28 Oct. 2003).

[12] M.C. Roco: International strategy for nanotechnology research and development. In: Journal of Nanoparticle Research 3 (2001), 5-6, pp. 353-360.

[13] BMBF: Nanotechnologie in Deutschland – Standortbestimmung, Bonn: Bundesministerium für Bildung und Forschung 2002.

[14] C. Roman: It's Ours to Lose – An Analysis of EU Nanotechnology Funding and the Sixth Framework Programme. Brussels: European Nanobusiness Association 2002. In: http://www.nanoeurope.org/docs/European%20Nanotech%20Funding.pdf (10 Nov. 2003). Other estimates cited there are significantly higher.

[15] M.C. Roco/W.S. Bainbridge (eds): Societal Implications of Nanoscience and Nanotechnology. Boston etc.: Kluwer 2001. In: http://www.wtec.org/loyola/nano/societalimpact/nanosi.pdf (22 Sept. 2003) (pp. 3-4).

[16] Roco/Bainbridge, loc. cit. (note 15).

[17] Some nanoparticles are already used e.g. in cosmetics, production is expected to increase strongly. See e.g. C.V. Howard: Nano-particles and Toxicity. In: No Small Matter II: The Case for a Global Moratorium – Size Matters! ETC Group Occas. Paper Series 7 (1) (2003). In: http://www.etcgroup.org/documents/Occ_Paper_Nanosafety.pdf (25 April 2003).

[18] Roco/Bainbridge, loc. cit. (note 15), pp. 13-16, and the contributions by Weil, Smith, Suchman, Meyer, Tenner.

tions have been inspired by the concept of molecular NT.[19] When the US NNI was founded and incorporated national security/defence issues on a high level, its focus was rather on medium-term implications of NT, however with openness towards revolutionary changes.[20] Unter the topic 'National Security', the first US workshop on converging technologies identified seven goals:[21]

1 Data linkage, threat anticipation and readiness (miniature sensors, high-speed processing and communication).
2 Uninhabited combat vehicles (air vehicles with artificial brains emulating a skillful pilot, similar for tanks, submarines etc.).
3 Warfighter education and training (inexpensive, high-performance virtual-reality computerised teaching, with speech, vision and motion interaction).
4 Chemical/biological/radiological/explosive detection and protection (micro sensor suites, protective masks and clothing, environmentally benign decontamination, physiological monitors and prophylaxis).
5 Warfighter systems (electronics with 100 times memory size and processing rates, flexible, thin displays or direct write onto retina, netted communication, weapons tracking targets, physiological monitors for alertness, chemical/biological agents, and casualty assessment; small volume, weight and power).
6 Non-drug treatments for enhancement of human performance (modify human biochemistry – compensate for sleep deprivation, enhance physical and psychological performance and survival rates from injury).
7 Applications of brain-machine interface (take brain signals nonintrusively, use with feedback for control of systems).

Arms-control considerations of NT are even scarcer.[22] This study presents an abridged overview of military R&D of NT and of potential military NT applications. Then it assesses the applications under the criteria of preventive arms control and derives recommendations for preventive limits.[23]

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19 Already in his first book Drexler wrote that based on the replicating-assembler breakthrough, a state could rapidly build high numbers of advanced weapons or wage a sort of germ warfare. Advanced artificial intelligence would be used for weapons design, strategy or fighting (Drexler 1986, loc. cit. (note 4)). For a discussion in the framework of international security see Gubrud, loc. cit. (note 6).

20 Roco/Bainbridge, loc. cit. (note 15), Ch. 2.

21 Roco/Bainbridge, loc. cit. (note 2), Section E.

22 If at all, arms control has been mentioned mostly in the context of molecular NT. Short and superficial arguments were given by Drexler and the Foresight Institute; more consideration was given in Gubrud, loc. cit. (note 6). The idea of concluding an 'Inner Space Treaty' after the Outer Space Treaty (S. Howard: Nanotechnology and Mass Destruction: The Need for an Inner Space Treaty. In: Disarmament Diplomacy, no. 65 (July-August 2002). In: http://www.acronym.org.uk/dd/dd65/65op1.htm (26 Aug. 2002)) is not very convincing.

23 Full detail is given in J. Altmann: Military Nanotechnology: Potential Applications and Preventive Arms Control. London/New York: Routledge 2006. Earlier articles include: J. Altmann/M. Gubrud: Risks from Military Uses of Nanotechnology – the Need for Technology Assessment and Preventive Control. In: M. Roco, R. Tomellini (eds.): Nanotechnology – Revolutionary Opportunities and Societal Implications. Luxembourg: European Communities 2002. In: http://www.ep3.ruhr-uni-bochum.de/bvp/riskmilnt_lecce.html (30 April 2004). J. Altmann: Military Uses of Nanotechnology: Perspectives and Concerns. In: Security Dialogue 35 (2004), 1, pp. 61-79.

2 Military Efforts for Nanotechnology

2.1 USA

2.1.1 Military NT Spending

As in other areas of military R&D, also in NT the USA is the most prominent actor. Already in 1996, nanoscience was named as one of six strategic research areas for Defense. Since the founding of the National Nanotechnology Initiative (NNI), the share of the Department of Defense (DoD) has been 1/4 to 1/3 of the total, second only to the National Science Foundation (Table 2.1). Table 2.2 shows the breakdown according to the phases of R&D: except for the first year, the share of basic research was around 45 per cent while applied research and advanced technology development got around 55 per cent. The categories further down the line that are directed towards a specific new product or upgrade[24] are not, or not yet, included.

Table 2.1 Funding for the NNI and the share of major agencies in US$ million (2000 to 2002: actual, 2003: appropriated, 2004: request).[25] The initiative started in fiscal year (FY) 2000.

Agency	**FY 2000**	**FY 2001**	**FY 2002**	**FY 2003**	**FY 2004**
National Science Foundation	97	150	204	221	249
Department of Defense	70	125	224	243	222
Department of Energy	58	88	89	133	197
National Institutes of Health [a]	32	40	59	65	70
Natl. Inst. Standards Technol.[b]	8	33	77	66	62
Natl. Air and Space Administ.	5	22	35	33	31
Environm. Protection Agency	-	6	6	5	5
Dept. of Homeland Security [c]	-	-	2	2	2
Department of Agriculture	-	1.5	0	1	10
Department of Justice	-	1.4	1	1	1
NNI total	270	465	697	770	849

a Department of Health and Human Service
b Department of Commerce
c Transportation Security Administration

24 6.4 Demonstration and Validation, 6.5 Engineering and Manufacturing Development and 6.7 Operational Systems Development (6.6 is Management Support). See J.D. Moteff: Defense Research: A Primer on the Department of Defense's Research, Development, Test and Evaluation (RDT&E) Program. CRS Report 97-316 (1999). In: http://www.NCSEonline.org/nle/crsreports/science/st-63.cmf (27 Nov. 2002).

25 Roco, loc. cit. (note 11); National Nanotechnology Initiative – Research and Development Supporting the Next Industrial Revolution – Supplement to the President's FY 2004 Budget. Washington DC: National Science and Technology Council 2003. In: http://nano.gov/nni04_budget_supplement.pdf (17 Nov. 2003) (pp. 5-8).

Table 2.2 Breakdown of military funding in the US NNI for basic research (6.1), applied research (6.2) and advanced technology development (6.3), for the various DoD agencies, in US$ million.[26]

Agency	**FY 2001 (Actual)**		**FY 2002 (Plan)**		**FY 2003 (Request)**	
Category	**6.1**	**6.2/6.3**	**6.1**	**6.2/6.3**	**6.1**	**6.2/6.3**
DUSD (R) [a]	36	-	26	-	28	-
DARPA [b]	28	12	9	88	11	90
Army	6	-	18	2	18	5
Air Force	6	4	8	7	13	5
Navy	31	-	21	1	26	5
Total	107	16	82	98	96	105

a DUSD (R): Deputy Undersecretary of Defense for Research

b DARPA: Defense Advanced Research Projects Agency

The DoD has founded three NNI Centers of Excellence: the Institute for Soldier Nanotechnologies at MIT (see Section 2.1.6), the Institute for Nanoscience at the Naval Research Laboratory (see Section 2.1.3) and the Center for Nanoscience Innovation for Defense at UCSB (see Section 2.1.7).[27]

2.1.2 NT R&D funded by the Defense Advanced Projects Agency

2.1.2.1 Overview of Programs and Budgets

Within the US Department of Defense, the Defense Advanced Research Projects Agency (DARPA) gets by far the highest share of NNI funding, with a clear emphasis on applied research and advanced technology development. Table 2.3 shows the DARPA program elements, their budgets for FY 2003, the number of projects of each and the respective number of programs. NT-related programs were found in 11 of the 13 program elements. Of the 313 DARPA programs, 36 were classified as related to NT in a narrow sense, and 51 in a broader sense. The former comprise expenses of US$ 468 million, the latter of US$ 547 million in FY 2003. This is 17 and 20 per cent, respectively, of the total DARPA budget of US$ 2,690 million.[28]

[26] M.C. Roco: National Nanotechnology Investment in the FY 2003 Budget Request by the President. 2002. In: http://nano.gov/2003budget.html (10 Sept. 2002).

[27] National NT Initiative, loc. cit. (note 25) (p. 34). On the civilian side, there are 11 Centers of Excellence – 7 funded by NSF and 4 by NASA.

[28] These figures are much higher than the one listed for DARPA ($ 101 m) under the NNI, see Table 2.1 and Table 2.2. The reasons are probably 1) that the respective program expenses contain work beyond NT and/or 2) that not all NT-related DARPA R&D come under the NNI heading.

Table 2.3 Overview of the DARPA funding structure for the period 2002 – 2005, evaluated from the Budget Estimates for FY 2004/5.[29] Excluding management support, three Budget activities comprise 13 program elements. Planned expenses for FY 2003 are shown in US$ million. Program elements consist of projects that contain programs; in each program, work is done by a number of contractors.[30] The final column gives the approximate numbers of projects that are related to NT in a narrow (bold) and a broad (medium typeface) sense and the respective funding in US$ million.

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29 Which DARPA programs come under the NNI heading could not be found easily. In order to get an overview of the NT-related work and an estimate for the corresponding expenditure, the budget estimates were studied (Fiscal Year (FY) 2004/FY 2005 Biennial Budget Estimates, Febr. 2003, Research, Development, Test and Evaluation, Defense-Wide, Vol. 1. Defense Advanded Research Projects Agency. 2003. In: http://www.darpa.mil/body/pdf/FY04_FY05BiennialBudgetEstimatesFeb03.pdf (16 Febr. 2004)). This 423-page document contains the Budget Item Justification Sheets for the individual DARPA programmes with short explanations. Excluding management, the 313 programs are grouped into 3 budget activities, 13 program elements (2 were finished in 2002) and 48 projects. In order to find whether a program is related to NT, all Sheets were examined. Programs that seemed to contain R&D in an area of NT proper were categorised as NT-related in a narrow sense. The second category comprises programs that deal with broader aspects of NT; this includes aspects of biology, artificial intelligence, cognitive science and robotics. Some of these may not yet use NT, but are likely to profit from it in the future, at least by smaller, more capable computers. This categorisation is superficial and somewhat arbitrary, and may have overlooked a few NT-related programs. Appendix 2 in Altmann, 2006, loc. cit. (note 23) shows the programs related to NT in a narrow and a broad sense with their budgets for FY 2003. The numbers of such programs are given in the last column of Table 2.3. Because the NT content in generic programs, such as for structural materials or small satellites, could not be separated, the expenses are an overestimate.

30 Program elements and projects finished before 2003 are not listed. Project and program counts do not include the Classified and Management Headquarters Program Elements.

Budget Activity	**Program Element**	**Expenses FY 2003 ($m)**	**No. of Projects**	**No. of Programs**	**NT-related Programs Narrow/**Broad **Number Funding**
Basic Research BA1	Defense Research Sciences	199	4	26	**15** / 2 **136** / 36
Applied Research BA2	Computing Systems and Communication Technology	409	9	58	**0** / 16 **0** / 153
	Embedded Software and Pervasive Computing	59	3	6	**0** / 3 **0** / 27
	Biological Warfare Defense	162	1	12	**1** / 1 **37** / 5
	Tactical Technology	170	6	40	**0** / 8 **0** / 27
	Materials and Electronics Technology	434	5	49	**12** / 3 **175** / 71
Advanced Technology Development BA3	Advanced Aerospace Systems	235	2	22	**1** / 8 **40** / 141
	Advanced Electronics Technologies	159	5	36	**7** / 2 **68** / 13
	Command, Control and Communication Systems	117	3	23	**0** / 3 **0** / 4
	Sensor and Guidance Technology	217	4	19	**0** / 0
	Marine Technology	36	1	4	**0** / 0
	Land Warfare Technology	166	3	12	**0** / 3 **0** / 82
	Classified Programs	288	?	?	? / ?
	Network-Centric Warfare Technology	0	2	6	**0** / 2 **0** / 0
RDT&E Management Support BA6	Management Headquarters	42	(1)	(1)	-
	Totals	**2,690 ***	**48**	**313**	**36** / 51 **468** / 547

* corrected for rounding error

2.1.2.2 Some DARPA Programs Narrowly Related to NT[31]

In electronics/computing, four programs look into Advanced Lithography to develop microelectronics (and other structures) with below 50 nm feature size. Fundamental alternatives to traditional computers are being pursued in several directions. Two programs are investigating spin-dependent electronics, materials and devices, such as spin transistors and quantum-logic gates. The Moletronics program is aimed at integrating molecules, nanotubes, nano-wires etc. into scalable devices; in the Molecular Computing program, combinatorial logic functions and memory are to be implemented in molecular components and integrated to form a demonstration processor (sequential logic/finite-state machine) capable of interpreting a simple high-level language. The new challenges for nanoscale interconnects will be tackled in the program Interfacing Nanoelectronics.

Much more specialised is the Nano Mechanical Array Signal Processors program that investigates arrays of up to 1024 mechanical nano-resonators for radio-frequency signal processing. Applications could be in wrist-watch-size, low-power UHF communicators or navigation (GPS) receivers. Another example is the Chip-Scale Atomic Clock where nano-resonators would be used together with photonic and microsystems-technology components. Using alkali atoms in very small cavities, the extreme accuracy of an atomic clock ($\pm 10^{-11}$ relative) would be packed into less than 1 cm^3.

Concerning materials, there are many activities. Within the Structural Materials and Devices program – which spans a very wide range –, R&D is carried out for large-volume, low-cost synthesis and assembly of nanomaterials and nanotubes with controlled attributes. Under Functional Materials and Devices, work is done for conducting polymers for analog processing, electroactive polymers for displays and muscle-like sensing and actuation for robots, high-density magnetic memory, microwave materials (ferrites, nanocomposite ferroelectrics, magnetodielectrics, negative-index materials), functional (conducting, piezoelectric etc.) fibres for electronic textiles.

Biology-related R&D has increased strongly in recent years. The Nanostructure in Biology program, for example, looks into nano-structured magnetic materials using nanomagnetics to understand and manipulate individual biomolecules and cells. Biocompatible, nanomagnetic tags, sensors and tweezers and a cantilever-based magnetic-resonance force microscope are to be built. With cantilevers, spectroscopy and imaging at atomic resolution is to be applied to molecules and nanostructures.

For routine analysis and design of integrated biological/chemical microsystems, the program Simulation of Bio-Molecular Microsystems aims at modelling and demonstration of molecular recognition, transduction into measurable electrical and mechanical signals using nanopores, micro-/nano-cantilevers and nanoparticles, and fluidic/molecular transport on the micro- and nanoscale.

The Bio Futures program focuses on computation based on biological materials and interfaces between electronics and biology. It will create 2-nm-diameter channels for

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[31] For detailed references, see the respective sections in Altmann, 2006, loc. cit. (note 23).

parallel processing of biomolecules, microfluidic devices for trapping insect embryos and create a multi-cantilever field-effect transistor for measuring single-cell physiology. Algorithms for analysis of neuronal spikes, cellular regulation and tissue differentiation in embryos will be developed.

Nano-structured material is being studied for use in a bio-inspired lens of variable refractive index and thus controllable field of view. Bio-molecular motors produce rotating or linear motion from chemical reactions on the nanoscale. The corresponding program is to study their properties and integrate them into laboratory devices. Hybrid biological/mechanical machines could actuate materials and fluids at scales from nano to macro; application could be for sorting, sensing and actuating.

The Biological Adaptation, Assembly and Manufacturing program studies adaptation to harsh conditions by specific genes to improve the stability of living cells and tissues, including platelets and red blood cells, and to reduce metabolism after injury. Assembly and manufacturing of bone, shell, skin etc. by nanoscale biomolecular networks is investigated.

In the Biological Warfare Sensors program, R&D of a great variety of systems is carried out. Narrowly related to NT are miniature sampling systems with new antibodies and 'designer small molecules' to bind specific agents (anthrax bacteria, pox viruses, toxins), and a bacterial biochip for the fast identification of species without the need for the DNA polymerase chain reaction.

2.1.2.3 Some DARPA Programs Broadly Related to NT[32]

Programs broadly related to NT may use NT indirectly or in the future. Many will incorporate NT at least in the form of improved computers, but a significant number also via sensors, structural materials and/or mechanical actuators. The former holds for artificial intelligence, the latter also for robotics. Biological, in particular biomolecular, work will profit from tools for investigation and manipulation at the nanoscale.

A special case is the program Quantum Information Science and Technology. It deals with theory and hardware components for quantum logic, memory, computing and secure communication. NT can come in via, for example, semiconductor nanostructures for quantum bits (electron states), single-photon sources and detectors.

In the field of artificial intelligence and cognition, DARPA programs are taking on some fairly bold tasks. There is no explicit reference to NT, but implicitly they rely on continuing increases in computer performance. Explicit goals are, e.g.: automation systems with 'interactions [that] are fundamentally like human-human interactions', 'software technologies [for] the autonomous operation of singly autonomous, mobile robots in partially known, changing, and unpredictable environments', 'Cognitive Computing Systems' that 'will reason, learn, and respond intelligently to things that have not been previously programmed or encountered'.

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[32] For detailed references, see the respective sections in Altmann, 2006, loc. cit. (note 23).

The area of autonomous vehicles/robots is covered by several programs. For Future Combat Systems, the Perception for Off-road Robotics program is developing and testing revolutionary perception systems (hardware and algorithms) under various terrain and weather conditions for uninhabited vehicles in combat, including collective action. The program Tactical Mobile Robotics aims at semi-autonomous robot teams for land forces. Autonomous Software for Learning Perception & Control is to program robots for navigation, learning of new tasks and adaptation to new environments. The program Unmanned Ground Combat Vehicle is developing and testing prototypes with improved endurance, obstacle negotiation and transportability (small size); wheels, tracks or walking/crawling may be used. Similar work is underway for uninhabited combat air vehicles, including rotorcraft, partly in co-operation with the services. Planning, assessment and control of distributed, autonomous combat forces such as uninhabited combat air vehicles is the subject of the program Mixed Initiative Control of Automa-Teams.

In the area of small robots, the Eyes-On program envisions an air-launched micro-unmanned air vehicle that provides real-time imagery to a fighter pilot for confirmation of targets, avoidance of collateral damage and bomb-damage assessment. Communication will be by line-of-sight radio-frequency link. By loitering in the target area, the system is also to be used for long-range weapons. For operations in urban exterior, underground and indoor environments, the Urban Robotic Surveillance System program will develop sensor systems and ground and air platforms, including communication routers and re-supply of fuel or power. Small robots are not explicitly mentioned, but the missions mentioned (route clearing, flank protection, tunnel clearing, scout and peacekeeping operations) make clear that they are part of the task. Software technologies for large groups of extremely small micro-robots that act in co-ordination are developed in the program Common Software for Autonomous Robotics. A human operator is to communicate with and control the swarm as a whole.

For military uses of outer space, the Space Assembly and Manufacture programme aims at very large, light-weight space structures. Micro-satellites for analysis of resources on non-terrestrial objects, miniaturised robotics for processing materials and building structures, propellants and power generation will be investigated.

In the biology area, the program Controlled Biological and Biomimetic Systems is devoted to understanding and controlling the basic functions of organisms. One- and two-way interfaces and communications with animals and 'animats' (artificial animals) will be explored. Projects come under the headlines of Vivisystems, Hybrid Biosystems and Biomimetics. The first is about investigating insects and using them as sentinels for chemical or biological agents. In the second area, one project is on microelectrodes in the brain of a monkey to derive motor signals and control a robot arm (see below); another project uses electrodes in the rat brain to control the motion of the animal. The third group covers, among others, flight stabilisation, artificial muscles and biomimetic robots moving under water, climbing like a gecko and flying like an insect.[33]

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[33] In this program, contracts have been let to two German institutions: Fraunhofer Institut für Autonome Intelligente Systeme (Scorpion, ambulatory robot) and Universität Bonn, Institut für Zoologie (insect infrared sensors). Controlled Biological and Biomimetic Systems. 2003. In: http://www.darpa.mil/dso/thrust/biosci/cbs.htm,.../biosci/cbs/overview.html, .../biosci/cbs/cprogram.html (13 Feb. 2004).

The idea of the Engineered Tissue Constructs program is to grow a three-dimensional human immune system from stem cells *ex vivo*, including interactive engineering of organs. It would be used to test vaccines and immunoregulators.

A few programs target the soldier's body. In order to have it adapt faster to extreme environments (temperatures, high altitudes etc.) and to increase survival after injury, research is being done on Metabolic Engineering for Cellular Stasis. A major focus is on long-duration preservation of blood and stem cells at reduced weight, to be re-activated on introduction into the body.

One goal of enhancing the human war-fighting efficiency is to prevent the effects of sleep deprivation. The program Continuous Assisted Performance aims at maintaining a high level of cognitive and physical performance over seven days, 24 hours each. To achieve this goal, methods from neuroscience, psychology, cell signalling and regulation, non-invasive imaging technologies and modelling will be used; among the means envisaged are magnetic brain stimulation and novel pharmacological approaches.

Another goal in providing 'superior physiological qualities to the warfighter' is to control energy storage and release in order to achieve, for example, 'continuous peak physical performance and cognitive function for 3 to 5 days, 24 hours per day, without the need for calories'. The Metabolic Dominance program will look at manipulations of metabolism, control of body temperature and ways of rapidly increasing the numbers and efficiency of muscle fibres and mitochondria.

The Brain Machine Interface program aims at recording and understanding the neural excitation patterns in the brain connected to motor or sensory activity. The motor signals could be read and used to control a system directly, without the 'detour' via the efferent nerves and the muscles in, for example, arm and hand. Thus, triggering a weapon or manoeuvring an aircraft could occur a few tenths of a second faster. For closed-loop control, an appropriate form of sensory (visual, postural, acoustic, other) feedback is to be developed. In experiments with about 100 microelectrodes in the motor cortex of rats and monkeys, the intended motion profile could be derived and a robot arm controlled successfully in one and three dimensions. The capability to read sensory signals in the brain could also be used for monitoring and communication. For human experiments and applications of reading or influencing brain patterns, non-invasive methods are envisaged for the time being. Whether external sensors or stimulators can provide the required spatial and temporal resolution, remains to be seen, however. As mentioned, the research is intimately linked with invasive animal experiments.

2.1.3 NT R&D at Military Research Laboratories[34]

Research at the nanoscale is a long-term focus of the Naval Research Laboratory (NRL) at Washington DC. Among the services' laboratories, it used to have the largest share of

[34] For details and references, see the respective section in Altmann, 2006, loc. cit. (note 23).

NT-related work.[35] In 2001, NRL founded a special Institute for Nanoscience, but work is also continuing in the Chemistry, Optics and Electronics Divisions. The research spans a vast range, from nanoassembly via nanooptics to neural-electronic interfaces and composite materials. The NRL maintains a list of contacts for the nanoscience and NT work in the DoD laboratories and the respective funding agencies.

The Army Research Laboratory (ARL) is doing 'aggressive' nanomaterials research. Beside electronics, further activities concern chemical and biological detection, decontamination and protection, armour as well as armour-piercing, new propellants. Beside its own research, ARL is also involved in the Institute for Soldier Nanotechnologies (see Section 2.1.6).

The Air Force Research Laboratory (AFRL) is also active in a variety of areas of NT, from self-assembly via electronics and optics to nano-energetic particles for explosives and propulsion. A NanoScience and Technology programme has been founded in the Materials & Manufacturing Directorate. NT-based materials, electronics, sensors etc. are also relevant for the Air Vehicles, Space Vehicles and Sensors Directorates.

2.1.4 Military NT R&D at National Weapons Laboratories[36]

The three laboratories responsible for nuclear-weapons R&D, Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL) and Sandia National Laboratories (SNL), have done NT-related work in the course of their usual activities. For stronger and more focussed activities, SNL and LANL jointly founded the Center for Integrated Nanotechnologies in 2002, with research themes: nano-bio-micro-interfaces, nanophotonics and nanoelectronics, complex functional nanomaterials, nanomechanics, theory and simulation. Much of this work seems to be general research not directed to specific military applications.

At LLNL, NT R&D was strengthened and co-ordinated following the founding of the NNI. In the Chemistry and Materials Science Directorate, the Materials Research Institute has one of its two foci in Nanoscience and Nanotechnology. In the same Directorate, there is a BioSecurity and Nanosciences Laboratory. Many NT-related projects are funded by the Laboratory-Directed R&D Program. Also here one gets the impression that a wide research area is being covered. One example of specific military relevance is work on new nanostructured high explosives using aerogel technology. Using variable composition, the energy release can be programmed. It is interesting that such R&D for new high explosives is also done under the Stockpile Stewardship Management Program that works for nuclear weapons. Computer modelling is used to investigate nitrogen fullerenes that promise high explosives of higher energy density.

One can assume that the three laboratories have additional secret programmes on military NT uses, not only in the field of nuclear weapons.

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35 J.S. Murday: Science and technology of nanostructures in the Department of Defense. In: Journal of Nanoparticle Research 1 (1999), 4, pp. 501-505. James Murday, long-time Superintendent of the Chemistry Division, has been involved on behalf of the DoD in the NNI from its conception.

36 For details and references, see the respective section in Altmann, 2006, loc. cit. (note 23).

2.1.5 Defense University Research Initiative on NT[37]

For basic NT research to be carried out at universities, the DoD has introduced the Defense University Research Initiative on NT (DURINT). The DURINT programme is administered through DARPA and the research offices of the Army, Navy and Air Force. In 2001, 17 equipment grants (total $7.25 million) and 16 research grants (total $8.25 million in FY 2001) were given; starting in FY 2002, up to $15 million per year were planned.

2.1.6 Institute for Soldier Nanotechnologies

In order to get NT-enabled systems closer to actual military use, the US Army is funding the Institute for Soldier Nanotechnologies (ISN). The ISN should 'serve as the Army's focal point for basic research into nanotechnology for application to the future soldier', and should perform co-operative research with industry and the Army R&D institutions. In March 2002, the Army selected the Massachusetts Institute of Technology (MIT) for the ISN. The five-year contract contains $50 million, and industry will contribute an additional $30 million.[38] With up to 150 staff, including 35 MIT professors from 9 departments, ISN will do unclassified basic research in seven multidisciplinary teams (Table 2.4), and its results will be published.

Table 2.4 Key soldier capabilities and multidisciplinary research teams of the ISN[39]

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37 For details and references, see the respective section in Altmann, 2006, loc. cit. (note 23).

38 Army selects MIT for $50 million institute. MIT News, March 13, 2002, updated March 14, 2002. In: http:// web.mit.edu/newsoffice/nr/2002/isn.html (15 March 2002). Army Teams with MIT to Establish ISN. U.S. Army News Release, March 13, 2002. In: http://www.dtic.mil/armylink/news/Mar2002/r20020313r-02-011.html (15 March 2002). D. Talbot: Supersoldiers. In: Technology Review, October 2002, pp. 44-51. The founding industry partners are: Raytheon, Dupont and the Center for Integration of Medicine and Innovative Technology.

39 Institute for Soldier Nanotechnologies: Research. 2002. In: http://web.mit.edu/isn/research/index.html (29 Oct. 2002). W.M. Mullins: Institute for Soldier Nanotechnologies. Viewgraphs presented at Defence Nanotechnology 2002, 31 Oct.-1 Nov. London: Defence Event Management 2002.

Key Soldier Capabilities	
Strong, lightweight structural materials for soldier systems and system components	
Adaptive, multifunctional materials for soldier systems and system components	
Novel detection and protection schemes for biological/chemical warfare threats and identification of friend or foe	
Remote and local soldier monitoring systems	
Remote and local, wound and injury triage and emergency treatment systems to enhance soldier survivability	
Novel, non-combat and combat performance enhancement systems for the soldier system that would improve soldier survivability en-route to and in the battlespace	
Multidisciplinary Research Teams	**Funding in FY 2002 (US$ million)**
1. Energy Absorbing Materials	2.45
2. Mechanically Active Materials & Devices	2.25
3. Sensors and Chemical and Biological Protection	2.75
4. Biomaterials and NanoDevices for Soldier Medical Technology	1.35
5. Processing and Characterization	2.70
6. Modeling and Simulation	1.38
7. Technology Transitioning – Research, Outreach, Teaming with Industry and the Army	1.44

The overarching goal is to 'dramatically improve the survivability of individual soldiers through nanotechnology research in three key thrust areas: protection, performance enhancement, and injury intervention and cure'.[40] A guiding vision is a battle suit that protects against bullets and chemical/biological warfare (CBW) agents, has strength to apply force for lifting heavy loads or to stiffen around wounds, and senses body state and CBW agents (Figure 1). Optically variable material is to change colour for adaptive camouflage and form reflective patterns at invisible-light wavelengths that can be interrogated remotely for identification of friend or foe. Whether such a suit will make possible leaps over 6-metre walls and whether the total carrying load of a soldier can be reduced from above 50 to 20 kg in 10 years, as suggested in first articles,[41] is open.

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40 Institute for Soldier Nanotechnologies: Mission and Overview. 2002. In: http://web.mit.edu/isn/overview.html (29 Oct. 2002).

41 A. Leo: The Soldier of Tomorrow – The U.S. Army enlists the Massachusetts Institute of Technology to build the uniform of the future. 2002. In: http://www.technologyreview.com/articles/leo032002.asp (8 April 2002). Army selects ..., loc. cit. (note 38).

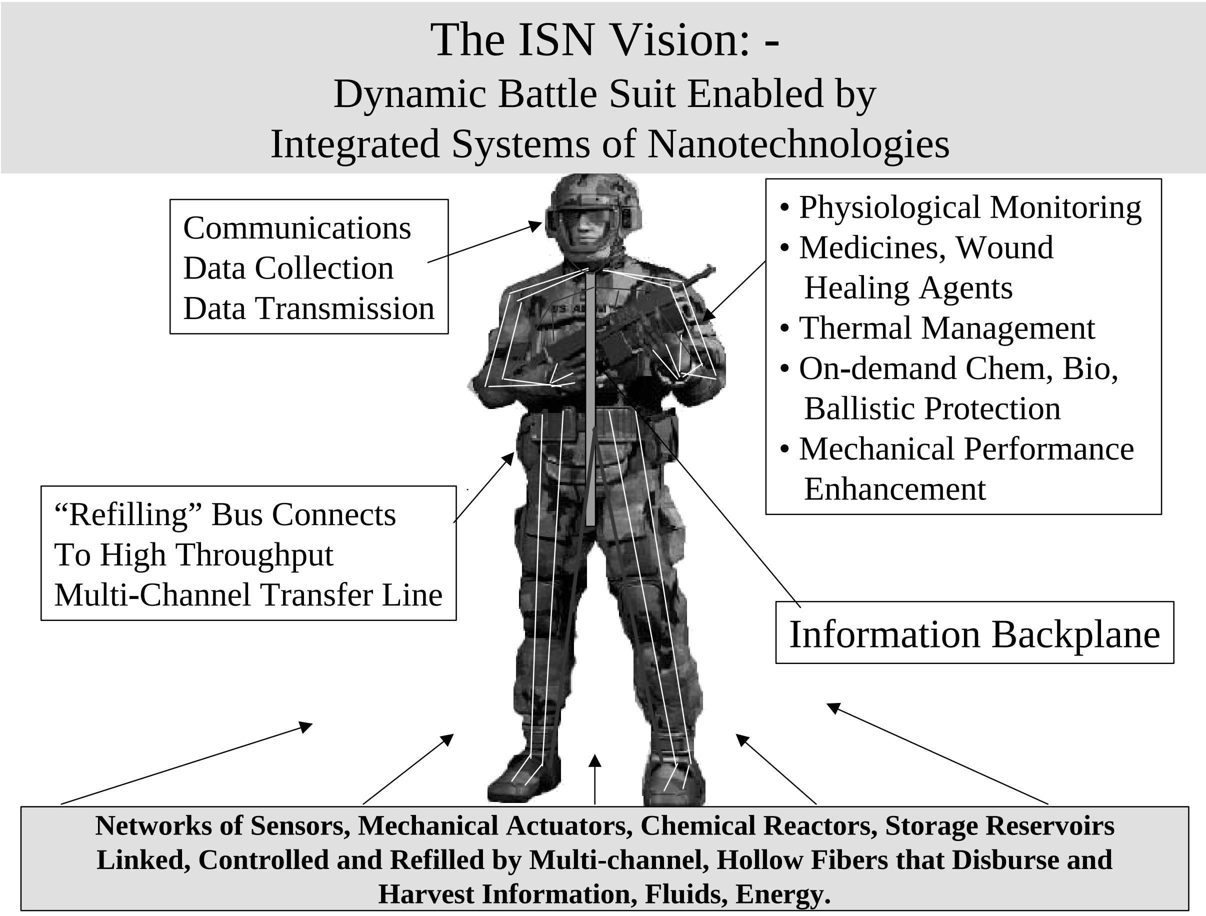

Figure 1 Battle-suit vision of the Institute for Soldier Nanotechnologies. (Provided by ISN, reprinted by permission)

2.1.7 Other Activities

In December 2002, the Center for Nanoscience Innovation for Defense (CNID) was founded at the University of California (UC).[42] $13.5 million has been given to the UC institutions at Santa Barbara, Los Angeles and Riverside; a second instalment is expected resulting in more than $20 million over three years. Additional participants include national laboratories, in particular Los Alamos National Laboratory, and ten industrial partners. A network is to be formed to keep the companies informed of the latest developments in science and technology.

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42 University of California, Riverside: New center for nanoscale innovation transfers knowledge from universities to industry. News Release, Dec. 10, 2002. In: http://www.newsroom.ucr.edu/cgi-bin/display.cgi?id=305 (3 Febr. 2003).

In order to accelerate utilisation of near-term improvements from NT R&D, the Tank-automotive and Armaments Command – Army Research, Development and Engineering Center (TACOM-ARDEC)[43] of the US Army at Picatinny Arsenal NJ has founded a Manufacturing, Research, Development, and Education Center for Nanotechnologies.[44] Focal areas of the NT centre are: advanced electronics for smart munitions, structural materials and processes (warhead components, gun system components, penetrators and armours), reactive materials and smart compounds, and fuse components.

2.2 Other Countries[45]

In Germany, military activities in NT have not really begun. As of the beginning of 2003, the Federal Ministry of Defence does not fund any research or technology activities in NT in a narrower sense.[46] It has tasked a major study on the 'Utilisation of Nanotechnology in Military Technology',[47] at a cost of about € 0.5 million. It will contribute to prepare decisions of the Defence Ministry about potential future activities in NT.[48]

In the United Kingdom (UK), the Ministry of Defence (MoD) has formed a Nanotechnology Panel.[49] NT research has been funded through the Corporate Research Programme at 1.5 million British Pounds (€ 2.1 million) in 2001; slight increase in the short term was foreseen. Because of the large world-wide investment, a major NT research programme is not necessary. The wide-ranging NT interests of the MoD include:[50]

- power sources; alloys, polymers, composites, textiles; explosives, pyrotechnics, propellants; self repair systems; weapons (intelligent, autonomous, accurate); stealth and counterstealth;
- secure messaging; global information networks, sensing;
- vaccines, medical treatment; wound repair, decontaminants; chemical/biological protective creams; 'lab on a chip' chemical/biological agent sensors.

Also, the potential of 'unethical use' leading to new biological and chemical weapons is mentioned.
Mixed funding from the MoD and Research Councils goes to NT Interdisciplinary Research Centres and to UK academia, and from the MoD to the firm QinetiQ and to industry. QinetiQ has founded QinetiQ Nanomaterials which grew out of work on energetic

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43 TACOM-ARDEC is responsible for explosives, warheads, munitions, weapons, fire control and logistics.
44 M. Devine: Manufacturing, Research, Development, and Education (RDE) Center for Nanotechnologies. Viewgraphs presented at Defence Nanotechnology 2002, 31 Oct.-1 Nov. London: Defence Event Management 2002.
45 In the course of this project, systematic collection of data on military NT R&D could not be done – and would probably have been impossible in many countries anyway. Consequently, this section presents the information that was found in easily accessible sources.
46 Bundesministerium der Verteidigung, Rü IV, letter of 30 Jan. 2003.
47 The study started in spring 2000 and was to be finished in 2004; it has been done by the Fraunhofer-Institute for Technological Trend Analysis, Euskirchen (INT), see also Wehrtechnische Implikationen der Nanotechnologie. 2003. In: http://www.int.fhg.de, search: Nanotechnologie (27 Oct. 2003). According to INT members (Dec. 2003), the study will be published.
48 It has to be noted that it is German policy in military technology to rely on results of civilian research wherever possible. Military funding goes only into those research and technology-development activities which are not sufficiently being done in the civilian realm.
49 Nanotechnology: Its Impact on Defence and the MoD. Nov. 2001. In: http://www.mod.uk/linked_files/nanotech.pdf. See also http://www.mod.uk/issues/nanotech/contents.htm (18 Nov. 2003).
50 D.E. Burgess: UK MoD's nanotechnology initiatives. Viewgraphs presented at Defence Nanotechnology 2002, 31 Oct.-1 Nov. London: Defence Event Management 2002.

materials using 100-nm particles. QinetiQ is active in the areas of: hybrids, nano-sensors, nano-magnetics, biomimetics, nano-carbon and nano-electronics.[51]

In France, a nuclear-weapon state with a strong tradition of military R&D, there are indications that significant efforts in NT have begun.[52]

In Sweden, an NT programme is being launched that is motivated on the one hand by the need for advanced equipment, but on the other hand by the needs for retaining an advanced defence industry base and an attractive R&D base. The Swedish Defence Research Organisation FOI has started a planning process for projects which should integrate industry, universities and defence. The first and second phases should start in July 2003 and July 2005, respectively. Technology demonstrations are foreseen for Fall 2008.[53]

No reliable information on military R&D of NT in Russia was found. Overview articles on NT work at large make clear that there is a wide range of civilian activities, even though hampered by economic difficulties.[54] Russian institutions take part in many international collaborations. In its National Security Concept of 2000, the Russian Federation stresses its concern, on a general level, with 'the growing technological surge of some leading powers and their growing possibilities to create new-generation weapons and military hardware'. Among the principles for use of military force, should that become necessary, it is stated that 'the restructuring and conversion of the defence industries should not come into conflict with the creation of new technologies and research-technical possibilities, the modernisation of weapons, military and specialised hardware, and the strengthening of positions of Russian producers on the world market of weapons'.[55] With a long tradition in military high technology and active NT R&D, there can be no doubt that Russia will be capable of using NT in various ways in the armed forces, should this become a high priority.

No hard information on military R&D for NT in China was found. NT research in general is very advanced in China; centres have been set up in the Chinese Academy of Sciences and various universities. Chinese institutions participate in international collaborations, and international conferences have taken place in China. The government has set

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51 P. Reip: Nanomaterials in Defence. Viewgraphs presented at Defence Nanotechnology 2002, 31 Oct.-1 Nov. London: Defence Event Management 2002. QinetiQ Nanomaterials – Ignitors. 2003. In: http:// www.nano. qinetiq.com/03_applications_knowledge/showcase.asp (18 Nov. 2003). QinetiQ was founded in July 2001 when the former Defence Evaluation and Research Agency was dissolved.

52 The second International Meeting on Micro and Nanotechnologies Minatec 2001 in Grenoble was supported, among others, by the French Defence Procurement Agency (Délégation Générale pour l'Armement, DGA); one 'regional day' organised by DGA was devoted to 'Science and Defence', with contributions from the Commissariat à l'Ènergie Atomique which is also responsible for nuclear weapons. Minatec 2001. In: http://www.minatec.com/ us/minatec.htm,.../minatec.pdf (18 Jan. 2001).

53 S.J. Savage: Evolution of a Swedish defence nanotechnology programme. Viewgraphs presented at Defence Nanotechnology 2002, 31 Oct.-1 Nov. London: Defence Event Management 2002.

54 E.g. G.M. Holdridge (ed.): Russian Research and Development Activities on Nanoparticles and Nanostructured Materials. Baltimore MD: International Technology Research Institute 1999. In: http://wtec.org/loyola/nano/ Russia/nanorussia.pdf (25 April 2003). R.A. Andrievski: Modern nanoparticle research in Russia. In: Journal of Nanoparticle Research 5 (2003), 5-6, pp. 415–418.

55 National Security Concept of the Russian Federation. Translation from Rossiiskaya Gazeta, January 18, 2000. In: http://www.fas.org/nuke/guide/russia/doctrine/gazeta012400.htm (5 April 2004). See also Military Doctrine of the Russian Federation. Presidential Decree of April 21 2000. In: http://www.dcaf.ch/publications/e-publications/ Rus_legal_acts/04_Military_doctrine.pdf (5 April 2004).

up a National Coordination Committee for nanoscience and nanotechnology; in the list of participating ministries and agencies, no defence-related institution was given explicitly.[56] However, it is probably safe to assume that the wording 'and so on' comprises the Ministry of Defence or the Commission of Science and Technology for National Defence. Relatively active in basic NT research and with expanding activities in military high technology at large, China is certainly able to develop all kinds of military applications.

Of the more than 30 countries with NT activities or plans, or the 15 most active in publications or patents, many will nearly exclusively focus on civilian products and markets. E.g. Taiwan and South Korea will likely continue their traditional economic path into the NT era. Japan is one of the biggest players in civilian NT, but has not been that active in military high technology in general. This will probably hold for NT in the future except if the general Japanese policy were to change.

In Israel, on the other hand, calls for founding a largely commercial NT initiative are having military connotations from the outset: Former Prime Minister S. Peres mentioned the possibility of military units without soldiers and noted the importance of Israel's nuclear option. The NT Committee established by the President of the Israel Academy of Sciences that called for a 5-year Israel NT Programme had one member from the Ministry of Defence and mentioned military development.[57]

In Australia, the Defence Science and Technology Organisation (DSTO) has prepared a first overview study on potential military applications of NT, with a view on the future land force; this effort will continue.[58]

For India, active in military high technology, possessor of ballistic missiles and nuclear weapons, one can assume that military R&D will soon turn towards NT. The other South Asian nuclear state, Pakistan, might follow.

Of the list of states of concern to the USA (Iran, Libya, North Korea etc.) none is remarkably active in NT at all, so indigenous development of military NT systems can practically be excluded for the foreseeable future. Of course, biomolecular research is possible for all of them already today, and growing availability of NT tools and methods will provide increasing capabilities for many state and non-state actors in the future.

2.3 International Comparison of Military NT Efforts

In order to compare the US spending for military R&D of NT, $ 243 million in 2003 (within the NNI, see Table 2.1), one can do a cautious guess of the 2003 expenses in other countries. Assuming that the UK funding of about € 2.1 million in 2001 were scaled up by

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[56] C. Bai: Progress of nanoscience and nanotechnology in China. In: Journal of Nanoparticle Research 3 (2001), 4, pp. 251-256.

[57] Nanotechnology holds a Key to Israel's Future. In: Jerusalem Post (6 March 2003). In: http://www.smalltimes.com/document_display.cfm?document_id=5613 (26 Sept. 2003). Executive Summary. 2001. In: http://www.nanoisrael.netfirms.com/executive_summary.htm> (26 Sept. 2003).

[58] J. Wang/P.J. Dortmans: A Review of Selected Nanotechnology Topics and Their Potential Military Applications. DSTO-TN-0537. Edinburgh South Australia: Systems Sciences Laboratory, Defence Science and Technology Organisation 2004. In: http://www.dsto.defence.gov.au/corporate/reports/DSTO-TN-0537.pdf (30 April 2004).

a factor of 1.5, one arrives at € 3.2 million. Absent more information, one can assume that NT-related military spending in France and the Netherlands is similar to that in the UK. In other European countries, it will be less. For Germany, it seems reasonable to assume a continued expense at the level of the previous years, around € 0.2 million. The sum over Western Europe is probably below € 15 million and almost certainly under € 20 million per year. This would mean that the US spending is above 12 to 16 times the West-European one.

Speculating about Russia's and China's expenditures, one can note that the overall military R&D budgets of the two other official nuclear-weapons states UK and France are about $ 4 billion and $ 3 billion per year, respectively, so that the NT-related expense given or estimated above is about one tenth of a per cent (it is 0.6 per cent for the USA with about $ 40 billion total). Assuming a similar ratio for Russia (total military R&D about $ 2 billion) and China (roughly $ 1 billion), one arrives at NT-related figures of $ 2 million and $ 1 million, respectively.[59] Doubling or tripling would raise the numbers to the level of the UK. Summing all the mentioned countries and allowing 10-20 additional ones with on average $ 2 million/year would yield a global expenditure outside of the USA of between $ 30 and $ 40 million per year. If that were true, the ratio between the USA and the rest of the world would be between 8:1 and 6:1.

As a more cautious estimate one can assume that the present spending ratio is between 4:1 and 10:1. However, the very small relative portion in the military R&D budget in all countries indicates that there is considerable leeway for increases – and experiences suggest that expenses will strongly increase as technologies move from research to development, and again from there to acquisition and deployment.

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59 Budget figures for 1999, Bonn International Center for Conversion: conversion survey 2001 – Global Disarmament, Demilitarization and Demobilization. Baden-Baden: Nomos 2001. The China estimate is from 1994, E. Arnett: Military research and development. In: SIPRI-Yearbook 1999 – World Armaments and Disarmament. Stockholm/Oxford: SIPRI/Oxford University Press 1999.

3 Potential Military Applications of Nanotechnology

3.1 Overview of Military NT Applications[60]

Potential military applications of NT were considered systematically, using existing sources as well as my own analysis. The results are presented here only in summarised form (Table 3.1), starting with the more generic applications, then proceeding to those that are rather specific of the military.[61] Rough estimates of the times to potential introduction are given, too. They depend on many factors, not the least the amount of funding, but one also has to expect surprises – on the one hand, unexpected breakthroughs or cross-fertilisation from a different area, or, on the other hand, unanticipated obstacles. Thus, the times are only given in coarse categories: within the next five years, five to ten years from now, ten to twenty years, and more than twenty years from now. In addition, there is a 'speculative' category for applications which cannot be excluded on the grounds that they violate the laws of nature. Some indication is also given on the expected degree of advance.

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60 For potential military applications of molecular NT, see Section 3.3 in Altmann, 2006, loc. cit. (note 23).

61 For the full considerations with references, in particular from US R&D, see Section 3.1 in Altmann, 2006, loc. cit. (note 23).

Table 3.1 Potential military NT applications, starting with more generic ones. The estimated time to potential introduction is designated by **A** (next 5 years), **B** (5 – 10 years from now), **C** (10 – 20 years), **D** (more than 20 years), **u** (unclear). Speculative applications where a time frame cannot be estimated are designated by '**??**'. The probable degree of advance is indicated in the right-hand column (+: modest, ++: significant, +++: radical).

Application **[Time]**	**Features, Examples, Use**	**Advance**
Electronics, photonics, magnetics **[A..B..C]**	Microelectronics, photonics, magnetics: smaller, more memory, faster, less power consumption; spin-/quantum electronics; small/light-weight/flexible displays	+++
Computers, communication **[A..B..C..D]**	Very small, highly capable, with sensors, actuators, embedded everywhere; ubiquitous flexible networks; large-scale planning, decision, management; quantum computing?	+++
Software/artificial intelligence **[A..B..C..D..??]**	Natural-language communication, translation, everyday knowledge; human-like interaction, perception, cognition, learning; autonomous decisions on many levels	++(+?)
Materials **[B..C]**	Composites with nanoscale additives or carbon nanotubes; amorphous metal; self-assembled structures; various functional, active and smart materials	+++
Energy sources, energy storage **[A..B..C]**	Fuel cells; solar cells; hydrogen storage; various small power generators	++
Propulsion **[B..C]**	More efficient reciprocating/turbine engines; small engines; electric motors; biologically inspired systems (large/small); more efficient rocket engines (large/small)	++
Vehicles **[B..C]**	Lighter, faster, more agile, longer range; electric propulsion	++
Propellants and explosives **[A..B]**	Better mixing of fuel and oxidiser, tailored energy density	+
Camouflage **[B]**	Fast change of colour (pattern) according to background	++
Distributed Sensors		
Generic **[A]**	Connected to pieces of equipment; surveillance at fixed locations – not autonomous	++
Battlefield **[B]**	Sub-mm size, scattered in high numbers, interrogation by laser beam or self-configuring radio network	++
Verification **[A]**	Centimetre size, NT only where special sensitivity	++

Armour, protection Heavy armour **[B]** Light armour/garments **[B]**	 Amorphous metal, additional outer layers/active armour Fibre composites, strong/light; nanostructures for absorption/reflection of electromagnetic radiation	 + ++
Conventional weapons Metal-less arms **[B]** Small guidance **[B]** Armour piercing **[A..B]** Small missiles **[B]**	 Nanofibre composites in barrels, locks, munition Inertial with microsystems technology, even in small projectiles Amorphous metal; nano-crystalline material; nanoparticles in shaped-charge explosive and liner Size below 1 m against aircraft, a few mm against persons	 ++ ++ + ++
Soldier systems **[B..C]**	Outside body: sensors for body functions, actuators for release of drugs, thermal management, stiffening material, exo-skeleton	++(+?)
Implanted systems, body manipulation **[B..C u]**	Modification of biochemical processes; targeted manipulation within cells; implants for monitoring body status, release of drugs; implants for nerve/brain contact; enhanced tissue, bones etc.	++(+?)
Autonomous systems **[B..C]**	Mobile on land, on/under water, in air, in outer space; traditional or new shapes/ modes of propulsion; unarmed or armed	++(+?)
Mini-/micro-robots **[B..C]**	Mobile on land, on/under water, in air; various propulsion modes; unarmed or armed; special: surgical operations within body	++(+?)
Bio-technical hybrids **[B..C]**	Small animals (rats, birds, fish, insects) with sensors, communication, nerve/brain contact for movement control; reconnaissance, small explosion, chem./biol. agent	++(+?)
Small satellites/space launchers **[B..C]**	Monitoring and communication using swarms, inspection and servicing of satellites, fast launch; anti-satellite use by manipulation after docking or by collision	++(+?)
Nuclear weapons Auxiliary systems **[A..B]** Computer modelling **[u]** Very small weapons **[??]**	 Safety, arming, fusing New warhead designs developed without tests Hypothetical pure fusion without fission trigger, e.g. ignited by antimatter	 + + ?
Chemical weapons **[B..C..D]**	Capsules, active groups for bonding, vectors for entry in body, cell, across blood-brain barrier, selective reaction, controlled persistence/reactivity	++(+?)

Biological weapons **[B..C..D]**	Capsules, active groups for bonding, easier entry in body, cells, brain, selective reaction, overcome immune reaction, controlled activity	++(+?)
Chemical/biol. protection/ neutralisation **[A..B]**	Sensors, membranes, absorption, neu-tralisation	++

In a few military applications (explosives, heavy armour, armour piercing, nuclear weapons), NT will bring modest improvement. In many more, significant advance is foreseen, and for several areas the adjective revolutionary seems justified – either because of radical advance in existing applications such as electronics, computers, materials, maybe also software, or because of qualitatively new options, as with soldier systems, body manipulation, large and small autonomous systems, bio-technical hybrids, small satellites and new chemical/biological weapons.

High efforts in R&D do of course not guarantee that the outcome will fulfil the original hopes. In some areas, the effectiveness or cost efficiency could turn out questionable. In particular, small systems could suffer from limited mobility, energy supply, communication capability or payload. Body manipulation might meet physiological or psychological problems. Artificial intelligence and autonomous systems could advance only slowly, as they did in the past.

The more generic military NT applications will have parallel civilian uses. Civilian R&D will be particularly active where mass markets are expected or where strong public interests exist – certainly with computers and software, some technologies of energy storage and conversion, medicine and maybe toy robots. In such areas, military applications will fast use civilian technology and may be driven by civilian R&D.

In the more specific military applications, however, where there will be little civilian demand or high technological risk, military R&D will certainly lead. In rare cases, costs may decrease after significant military investment and a civilian market may become possible. This might apply to mini-/micro-robots.

3.2 Countermeasures Against Military NT Systems

Assuming widespread NT application in the military as mentioned in Section 3.1, defence and offence against hostile NT-based systems get central importance. This holds in particular for new systems such as mini-/micro-robots or chemical/biological agents. It would hold all the more if molecular NT became possible. Because of the wide variety of effects, various countermeasures are to be expected that would make massive use of NT themselves, of course at the respective technological level available. Some methods of countering NT-based weapons could be:

1 general strategies:

- faster information processing, more autonomous decisions,
- withdrawal of humans, use of mostly artificial systems,
- redundancy – increase number of own systems,
- dispersal of functions to many smaller systems,
- hide better by smallness and camouflage;

2 passive protection:

- observe the environment, get out of the way,
- sieves with molecule-size pores against penetration through openings,
- complete encapsulation, also of sub-systems,
- make adhesion to surfaces more difficult,
- hardening (e.g. nano-layer against mechanical abrasion or heat, stronger structures against impact);

3 active defence:

- small missiles/projectiles against approaching mini-/micro-vehicles,
- active surface for destruction of approaching or adhering objects,
- micro-/nano-robots as 'guards' (on outer surface, inside own systems/positions; within body/cells),
- preventive 'inoculation';

4 offence strategies (using various means):

- counterattack,
- pre-emptive attack,
- preventive attack.

The effectiveness of weapons vs. countermeasures is unclear at present. Similarly, one cannot predict which mixture of defensive and offensive means and methods may develop. However, there are no indications of defence dominance, so that counterattack and pre-emptive or even preventive attack will likely continue to play an important role in armed conflict.

4 Preventive Arms Control for NT

4.1 Preventive Arms Control: Still Valid After the Cold War?[62]

The general concept of preventive arms control dates back to the Cold War, where one can find many instances when the military situation became more unstable and dangerous after new military technologies were introduced, such as the hydrogen bomb, the long-range ballistic missile or multiple warheads on nuclear missiles. After deployment, agreement on reduction was very difficult to reach. The goal of preventive arms control is to avoid similar situations and to prevent new military technologies with potentially dangerous consequences from being realised in the first place, before they are being deployed. Even though the Cold War is over, the concept of preventive arms control is still valid for several reasons:

- Whereas armed conflict between USA, Russia and China seems remote at present, nevertheless these states keep their respective forces and train them for such a contingency. At the fundamental level, nuclear deterrence is still at work, too. Thus, motives to use new technology in order to prevail in such a war – or to prevent that an opponent can prevail – continue to exist. As a consequence, a competition in military technology is in some way going on all the time. With the outlook for revolutionary change in many fields, NT could intensify this process drastically – accelerating arms races could develop in all areas of military NT applications.
- One can even argue that to some extent, a similar mechanism is in effect between partners in a military alliance. On the one hand, there is the principal possibility that the political situation in the partner country may change at some time in the future, so that armed conflict and military threats can no longer be excluded completely.[63] On the other hand, arms-race pressures on allies work via the common potential opponent(s). And for the less fast advancing partners there is the argument that for co-operation in armed conflict, standardisation and interoperability require preventing too large a gap to a technologically leading partner.[64] Thus, it is not difficult to conceive of a rush towards, e.g., autonomous combat vehicles, should one country start introducing them, not only between potential opponents, but also among partners – and the same for micro-robots, mini-missiles etc.
- A counter-argument could be that the strongest security threats at present do not stem from the states with strong armed forces, but from terrorist groups and

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62 For a detailed discussion of the concept and design of preventive arms control, see Ch. 4 in Altmann, 2006, loc. cit. (note 23).

63 This is rarely discussed in public, but nevertheless is likely to be part of fundamental convictions. See P.E. Tyler: U.S. Strategy Plan Calls For Insuring No Rivals Develop. In: New York Times, 8 March 1992.

64 While such arguments are often made, e.g. in the debate on allegedly insufficient technological efforts of the European members of NATO versus the USA, it is remarkable that there is no discussion that the USA should decelerate its rate of innovation in the interest of better co-operation.

failed states – and these could not be partners in preventive limitation. However, such groups and states are unlikely to be able to develop NT-based new weaponry by themselves. The much more likely scenario is that military technology and weapons developed in the high-technology countries will be exported or otherwise proliferate to end up in the hands of non-state actors. As a consequence, limits agreed among the NT-capable countries will have a significant effect in limiting access of terrorists and groups in failed states, in particular if preventive limitation is being supplemented by special efforts to limit dual-use exports.[65]

4.2 Preventive Arms Control: Process and Criteria

Preventive arms control consists of four steps:

1 prospective scientific analysis of the technology in question;
2 prospective analysis of the military-operational aspects;
3 assessment of both under the criteria of preventive arms control;
4 devising possible limits and verification methods.

These steps are to be carried out in interdisciplinary research, interacting with practitioners. In the optimum case, nations would afterwards start negotiating the corresponding agreement. To find out where military-relevant technologies may entail special dangers so that considerations on preventive limits should take place, a set of criteria in three groups has been developed:[66]

I Adherence to and further development of effective arms control, disarmament and international law

- Prevent dangers to existing or intended arms-control and disarmament treaties
- Observe existing norms of humanitarian law
- No utility for weapons of mass destruction

II Maintain and improve stability

- Prevent destabilisation of the military situation
- Prevent technological arms race
- Prevent horizontal or vertical proliferation/diffusion of military-relevant technologies, substances or knowledge

III Protect humans, environment and society

- Prevent dangers to humans
- Prevent dangers to environment and sustainable development
- Prevent dangers to the development of societal and political systems
- Prevent dangers to the societal infrastructure.

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65 The problem of mistrust of the user countries in the motives of the supplier countries needs to be solved, optimally by a regime including the former.

66 G. Neuneck/C. Mölling: Methoden, Kriterien und Konzepte für Präventive Rüstungskontrolle. In: Wissenschaft und Frieden, Dossier Nr. 38, 2001.

4.3 Applying the Criteria to NT[67]

In order to find out the problematic applications, the potential military NT applications presented in Chapter 3 are considered under all the criteria. Only the direct and more or less obvious consequences are taken into account, except for criteria group III on humans, environment and society that deal mostly with peace-time consequences. Only the negative evaluations are mentioned here.[68] In a few areas the evaluation differs according to specific applications. Thus, sub-groups are introduced with: sensors, new conventional weapons, autonomous systems, nuclear weapons.

4.3.1 Criteria Group I: Adherence to and Further Development of Effective Arms Control, Disarmament and International Law

4.3.1.1 Prevent Dangers to Existing or Intended Arms-Control and Disarmament Treaties

Negative effects are possible with new conventional weapons if they are used to circumvent the Treaty on Conventional Armed Forces in Europe (CFE) or future regional agreements for the control of small arms and light weapons. If new weapons contain less/no metal, verification of such agreements (by induction detectors or x-raying machines) would become more difficult. The same argument would hold for small missiles. The CFE Treaty could also be undermined by armed autonomous systems. Armed mini-/ micro-robots could have the same effect and could also endanger the Anti-Personnel Mine Convention since due to their mobility and other characteristics, they would not qualify as a mine, but could nevertheless function as such.[69]

Small and/or more autonomous satellites, if used for anti-satellite attack, would counteract the general ban on space weapons that the international community has striven for since decades.

Vastly extended computer modelling of nuclear weapons can lead to new warhead designs that could on the one hand undermine the Comprehensive Test Ban Treaty. If the models became so detailed – and maybe verified with data from historical tests – that confidence is sufficiently high, then the new designs might even be built and deployed without tests. While formally complying with the Comprehensive Test Ban Treaty, this would violate at least the spirit of the Nuclear Non-Proliferation Treaty that stipulates good-faith negotiations towards nuclear disarmament. The same holds for very small nuclear weapons. New chemical or biological weapons would contravene the Chemical and the Biological Weapons Conventions.

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[67] For application of the criteria to molecular NT see Section 6.2 in Altmann, 2006, loc. cit. (note 23).

[68] For the full consideration and a summarising table, see Sections 6.1 and 6.3 in Altmann, 2006, loc. cit. (note 23). In some cases, fulfilment of a criterion is not NT-specific (e.g., new biological warfare agents could come about by 'traditional' molecular-biology research and development (R&D)); however, NT will significantly accelerate R&D in many areas and may make many applications much more economical. The dividing line between direct and indirect effects is fuzzy. A certain arbitrariness in assigning negative/neutral/positive values to certain technologies or military applications is unavoidable, e.g. due to special cases or exceptions.

[69] Art. 2 (2) of the Anti-Personnel Mine Convention: ' "Mine" means a munition to be placed under, on or near the ground or other surface area and to be exploded by the presence, proximity or contact of a person or a vehicle.'

4.3.1.2 Observe Existing Norms of Humanitarian Law

New types of conventional weapons could in principle contravene the rule against superfluous injury or unnecessary suffering, e.g. if NT-enhanced projectiles act similarly to dum-dum bullets. Since states are under an obligation to check consistency with humanitarian law for all new weapons, means and methods of warfare,[70] one can expect caution here. Nevertheless, the international community should monitor this area and take action, if required, in particular because there may be differences of opinion. On the other hand, NT will allow much more precise targeting with correspondingly reduced destructive power so that wounds could be smaller and collateral damage less, with a positive effect on humanitarian law.

Body manipulation and implanted systems could have negative results if aggressiveness in fighting were increased by electrical or hormonal stimulation to such an extent that protection of non-combatants or combatants *hors de combat* is no longer warranted.

Great problems can be foreseen with armed autonomous systems, including mini-/micro-robots that are armed or are used to designate targets. Discriminating between combatants and non-combatants, recognising legitimate military targets or recognising the condition *hors de combat* (wanting to surrender, unconscious or unable to fight by injury or illness) are complicated tasks that require a more or less human level of intelligence. For quite some time – at least one decade –, artificial systems will not reach such a level. At least until then, autonomous decisions about weapon use and autonomous picking of targets for attack by other weapons would contravene humanitarian law.

Hypothetical very small nuclear weapons, even though much below the explosive yield and radioactive fallout of the traditional large ones, could still create unnecessary suffering and affect non-combatants disproportionately. New chemical or biological weapons would violate the rules banning such methods of warfare.

4.3.1.3 No Utility for Weapons of Mass Destruction

Much more powerful computers will allow markedly improved modelling of nuclear explosions that could lead to new warhead designs. The hypothetical very small nuclear weapons, while blurring the distinction between conventional weapons and weapons of mass destruction, would at least in the upper end of their yield (above, say, 10 t TNT equivalent) nevertheless still qualify as the latter.

New chemical and biological weapons would count as weapons of mass destruction if they can attack many target humans, animals or plants. Even if NT and biomedical advances could provide mechanisms for very selective uses, maybe even against only one individual, the knowledge gained in the R&D could be used for agents and carriers targeting larger collectives.

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70 Art. 36 of Additional Protocol I to the Geneva Conventions of 1949.

Chemical weapons that would confuse large numbers of people for a sufficiently long time could indirectly, by the breakdown of societal production and distribution systems, cause mass death.

4.3.2 Criteria Group II: Maintain and Improve Stability

4.3.2.1 Prevent Destabilisation of the Military Situation[71]

Much more powerful computers could be used for more precise targeting which could improve the outlook for surprise attacks. Much increased capabilities in artificial intelligence, used in battle management, could lead to a higher reliance on automatic decisions whereby opponents in a crisis might faster slide into war; however, in particular at the pre-conflict stage, humans will try to keep the situation tightly under control. Faster propulsion and lighter, more agile vehicles can reduce the travel and thus warning times.

Battlefield sensors would help to locate targets, making easier fast precision attacks. New conventional weapons with higher speed and more precise targeting would have some negative effect. Strong destabilisation would result if conventional attack against nuclear weapons carriers and strategic command-and-control systems became available.[72]

Armed autonomous systems would act and react with very short time lines. Deployed at close mutual range, strong pressures for fast attack would be at work between opponents of roughly comparable technological capabilities. Movements or actions mistaken as (pending) attack could easily lead to the start of hostilities. The same holds for accidents or errors in the warning systems. Even stronger destabilisation would follow from mini- and in particular micro-robots that are armed or are used to designate targets, because they could be sent covertly already before armed conflict, ready to strike (or guide strikes) at important nodes from within at any time. Surprise attack on the command, control and communication system, e.g. on sensors, communications, weapons-control equipment, could drastically reduce one's capabilities. The warning time could be extremely short. In parallel, strong motives would exist to send mini- and micro-robots for reconnaissance into the opponent's territory, some in advance, others at the time. Even if some of them would be noticed, differentiating between systems for reconnaissance and for direct attack would be extremely difficult. As a consequence, armed autonomous systems and mini-/micro-robots at large would create great uncertainty; human commanders would be correspondingly nervous, and equipment would be programmed to

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71 Stability refers to the situation between actors that see themselves as potential opponents in armed conflict so that military preparations are part of the mutual relations. General military stability exists if neither side can expect a successful outcome if it started war. If the mutual relations deteriorate, the short-term notion of crisis stability becomes important. It refers to the possibility of mounting a surprise attack, in particular reducing the opponent's armed forces so that success in defence becomes questionable; in nuclear strategy, the question is whether a second strike can still be delivered (deterrence). When one side fears a successful surprise attack, it is under pressure to pre-empt that by itself attacking first. A situation where both (or more) sides have strong motives for pre-emptive attack is highly unstable.

72 See E. Miasnikov: Precision Guided Weapons and Strategic Balance (in Russian). Dolgoprudny: Center for Arms Control, Energy and Environmental Studies at MIPT 2000. In: http://www. armscontrol.ru/start/publications/ vto1100.htm (18 April 2002).

operate fast. Unintended action-reaction cycles between the mutual systems of warning and attack have to be feared.

In outer space, (swarms of) small satellites could provide improved detection capabilities for targets on the ground and in the air, and more capable communications channels, that could be used for surprise attack on earth. Much more destabilising would be their capacity to attack other satellites, either by collision at high relative velocity, or by manipulation after rendezvous and docking. This could knock out the various reconnaissance, early-warning and communication satellites that are of central importance for warfare on earth for the largest military power(s), including command and control of nuclear weapons. Whereas the strongest destabilisation is expected if small satellites are already deployed in space, they could also be lifted there on short notice by small launchers. These could take off from nearly anywhere, including ships and aircraft. Their travel time to low earth orbit (300 to 2000 km) would be many minutes, to geostationary altitude a few hours, with corresponding warning times.

With respect to nuclear weapons, direct reduction in stability, in particular regarding deterrence against nuclear-weapons use, would follow from very small nuclear warheads. With a blurred distinction from conventional weapons, the reluctance to use them would be lower than with traditional nuclear weapons, making actual employment more probable. This crossing of the nuclear threshold could act as a precursor to the use of larger nuclear weapons.

In a similar vein, new chemical or biological weapons that would seem to make their use better manageable, targeting only the intended group(s) and saving one’s own forces and population, could undermine stability.

4.3.2.2 Prevent Technological Arms Race[73]

With respect to the various potential military NT applications, arms-race motives exist practically for all of the more generic and all of the more specific uses. Nearly everywhere there is the promise that traditional military missions can be fulfilled better or that new ones become accessible. Arms-race motives are particularly urgent where threats to one’s own forces or restrictions of their operations can be foreseen.

4.3.2.3 Prevent Horizontal or Vertical Proliferation/Diffusion of Military-relevant Technologies, Substances or Knowledge[74]

Concerning potential military uses of NT, vertical as well as horizontal proliferation of systems, technologies, substances and knowledge has to be feared in all areas. Transfer

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[73] If one among several potential opponents introduces new technologies into its armed forces, strong motives to do the same exist for the others. This holds in general and – because of the long lead times – works already on the stages of R&D. As discussed in Section 4.1, a similar mechanism is in effect even between partners in a military alliance.

[74] Non-proliferation became a goal of arms control with the rise of nuclear weapons. Here, horizontal proliferation means that additional countries acquire/build nuclear weapons whereas vertical proliferation refers to states with nuclear weapons acquiring more or new types of them. Diffusion refers to a less tangible process where technologies, substances or knowledge spread. These concepts can be generalised to other military-relevant technology areas.

of systems will be the easier the smaller they will be. Diffusion will take place particularly in the more generic fields where widespread civilian applications are foreseen.

4.3.3 Criteria Group III: Protect Humans, Environment and Society

4.3.3.1 Prevent Dangers to Humans[75]

New materials could bring risks to human health, e.g. by nanoparticles travelling across boundaries in the body and interacting with cell processes, the same could apply to new propellants and explosives. New conventional weapons could bring dangers to humans if they proliferate to criminals; this could apply to small arms and maybe light weapons. In particular metal-free arms or small missiles would provide new options for terrorist attacks.

Armed autonomous systems would probably be reserved for armed conflict – internal law-enforcement institutions would likely keep a human in the decision loop all the time for constitutional reasons. However, the constitutional argument does not hold in operations other than war, e.g. in an occupied country, so there is a grey area here where humans might become unjustifiably endangered. Armed and unarmed autonomous systems could also cause accidents in peacetime: testing would probably be limited to military property or, in international territory, to specific areas with advance warning. However, there would also be routine patrolling operations along borders, on and in the oceans and in the air.

Mini-/micro-robots acting as weapons would produce dangers if they became available for criminals, in particular terrorists. The same would apply to new chemical or biological weapons. Attacks could be directed at single persons – small robots could sneak into a building, injecting a drug during sleep, firing a small projectile or setting off a small explosion close to a person's body. Sophisticated chemical or biological agents could be used against selective targets or for mass attacks, e.g. poisoning drinking water or food. If new weapons and autonomous armed systems could be strictly limited to the military, they would not count under this criterion. With chemical and biological weapons, however, there is the additional risk of unintended release from military production or storage facilities.

Body manipulation and implanted systems could produce dangers to soldiers in peacetime if they bring about secondary effects. More important could be the indirect consequences if military R&D and application of body manipulation contributed to general use in society with too few restrictions (see Section 4.3.3.3). Many negative secondary effects on body and mind are conceivable, similar to and beyond those of addictive drugs.

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[75] This criterion applies mainly to peacetime – it is about (new) military technologies or substances negatively affecting people, mostly in civilian society. Armed conflict is by definition connected to dangers to soldiers and practically always brings dangers also for non-combatants – but these aspects are being dealt with by the criterion about the law of warfare, see Section 4.3.1.2.

4.3.3.2 Prevent Dangers to Environment and Sustainable Development[76]

New materials as well as propellants and explosives could damage life processes in plants and animals.

Very small nuclear weapons would still produce and release radioactive material that would pollute the affected area. New, highly selective chemical and biological weapons that would be used only in minute quantities could leave the environment untouched; however, others could have negative effects, e.g. if directed against widespread plants.

4.3.3.3 Prevent Dangers to the Development of Societal and Political Systems[77]

If vastly more capable computers and communication devices, together with corresponding software, developed in the military, were used for tracking and surveillance of individuals, which would become possible in the context of ubiquitous computing, they would infringe on freedom and privacy. Much more capable artificial intelligence could be used to mine data bases for information about individuals, corporations and other institutions.

Sensors developed originally for battlefield monitoring, suitable to be scattered, some extremely small, competent in finding and recognising targets at a distance, could be used for eavesdropping and tracking of individuals and vehicles at least by state agencies. Should the sensors become cheap and numerous, also private entities and criminals could use them, for private espionage or for other crimes. Mobile mini-/micro-robots would provide a markedly higher potential for intrusion into privacy and eavesdropping. If small enough, they could covertly enter offices or houses – even through the crack under the door, or through an open window. Small robots could also act – e.g. steal, disrupt or destroy something. Injuring or killing people could be done while they sleep or, similar to an insect – and maybe even using an insect(-like) body –, at any time and any place, in public or private. Tracing back the originator could be very difficult. If such possibilities arise, one can expect countermeasures such as seals for openings and detectors for small mobile objects. Nevertheless, a feeling of endangered privacy and insecurity is probable with a high burden on society. Negative influences on democratic processes can be expected, too.

If new conventional weapons fall into private hands, security in society could suffer. Checking for arms that are not visible by x rays and metal detectors would require more intrusive procedures.

Body manipulation and implants in the military would at first affect only a small part of society. Soldiers might accept them voluntarily because they would provide better fighting efficiency or faster treatment after injury. After some time, or in countries with less re-

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[76] This criterion also deals mainly with peacetime effects, since in armed conflict damage to the environment can hardly be avoided. However, the Environmental Modification Convention of 1977 and the Additional Protocol I to the Geneva Convention (Art. 35) prohibit widespread, long-lasting or severe effects.

[77] This criterion deals mainly with the internal processes within societies in peacetime. These will mostly be affected by military-technology applications in an indirect way.

spect for human rights, soldiers might be ordered to get specific drugs or implants, similar to preventive vaccinations. However, this touches fundamental questions whether non-medical body manipulation should be allowed, and if so, what types. Up to now, medical as well as general ethics treats the human body as a sanctuary; invasion is only justified if there are medical reasons, that is for therapy – trying to restore a status of health. Enhancement is not yet really possible which contributes to the reluctance towards it. Concerning genetic improvement – that would be possible already today –, there is general condemnation. In sports, doping is penalised. However, the rejection of body improvement is not absolute, as shown by cosmetic surgery, Viagra and widespread use of Ritalin or alertness drugs.

With medical progress, the potential for enhancement of healthy people will grow. Some applications might be considered useful, e.g., an implanted medical data chip (already possible today) or a memory chip with contacts to the brain (very far off). It is easy, however, to conceive of abuse and severe dangers. Wireless identification devices could be used to track people. Corporations providing the 'program' for implanted sensory and emotion devices could manipulate people. Stimulation of a happiness centre in the brain could make people virtually addicted. Enhanced organs, delayed ageing etc., even if individually attractive at first sight to many, need not be judged positively if the overall societal outcome is taken into view. The changes of human nature that may become possible are profound. Deeper ethical questions will be posed than with stem-cell research or human cloning.

All these are purely civilian problems. The extent to which non-medical body manipulation should be allowed should be considered and debated in society at large and its democratic decision-making bodies. However, widespread military uses could undermine and pre-empt an open-ended societal debate by accustoming people to the idea and its realisation. Military body enhancement would create facts that may be difficult to impossible to revoke. Thus, it poses dangers to societal and political systems.

Should very small nuclear weapons become possible, strong dangers to societal and political systems could ensue, but only in case they became available to non-state actors. While this possibility is doubly hypothetical, new chemical and biological weapons would offer many possibilities for terrorist attacks and extortion with the corresponding dangers for society.

4.3.3.4 Prevent Dangers to the Societal Infrastructure [78]

Among new conventional weapons, metal-less arms, small guidance and small missiles, if diffusing into the hands of criminals, could be used for more effective/more secretive attacks on the societal infrastructure. The same holds for mini-/micro-robots – those with weapon function could be used directly, those without weapon function could nevertheless be used to transport highly toxic agents or damage central components after entering into installations. Small satellites and launchers could attack commercial satellites

[78] As the other criteria in this group, this one mainly concerns peacetime. The infrastructure is providing basic services, such as transport and communication, and goods, such as water and electricity. Massive disturbances can ensue from breakdowns. Thus, the societal infrastructure may be a target in particular for terrorists.

that fulfil an important role in the global communication infrastructure – such attack could also affect states that are not a party to an armed conflict. Armed autonomous systems would not easily become available to criminals. However, they could damage infrastructure by accidents, in particular by crashes from the air.

Very small nuclear weapons, if feasible, would present strong dangers to infrastructure, but only if they became available to non-state groups. New chemical and biological weapons could be delivered via drinking water and could thus be used to shut down the supply.

5 Options for Preventive Limits on Military NT

When discussing how the most problematic applications identified in Section 4.3 could be limited preventively, arguments for limits are to be balanced with potential positive uses. In addition, aspects of effective, but simple verification needs to be considered.[79]

5.1 Distributed Sensors

Among distributed sensors, the strongest dangers for military stability as well as for privacy derive from those developed for use on the battlefield. As the size would decrease, the risks would grow, since the sensors would be more difficult to find and could be used in higher numbers. Introduction of very small military systems would greatly aggravate the problems of verification. Distributed sensors for general purposes would be much less capable of doing general surveillance in a more or less autonomous mode. Often, they would be built into a larger piece of equipment, power for information transfer could be provided by wire or from an external, local radio-frequency field.

As a consequence, limitation efforts should focus on distributed battlefield sensors. A total ban seems unrealistic, since several types of battlefield sensors are already deployed with armed forces – all of them of macroscopic size (many cm). In principle, many different characteristics could be used to define qualitative limits, such as the variable that is sensed, the mode of information transfer (e.g., only by cable, for radio transmission a maximum data rate) or a minimum allowed size. The former limits would be difficult to agree on and to verify. Because the dangers in most part derive from the smallness of NT-enabled new sensors, a simple size criterion seems most practical, combined with a capability of autonomous functioning and information transfer over some distance. As a consequence, one arrives at a complete ban on self-contained sensor systems which are smaller than a certain size limit (3 to 5 cm). It would not affect smaller sensors that are built into larger systems.[80]

At present, there are not many civilian needs for smaller sensors. Should an urgent need be felt, then exceptions need to be defined by clear qualitative and quantitative limits, with technical precautions against undermining of the main goal.[81] Some existing small monitoring and eavesdropping devices ('bugs', for insertion into telephone sets, sticking to the underside of tables etc.) would fall under the ban. Small sensors used legally by law-enforcement agencies could be exempted.[82]

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79 Full detail is given in Section 6.4 in Altmann, 2006, loc. cit. (note 23).

80 One could also restrict the ban to include only sensors for outside use, but given the present emphasis on urban warfare, this would exclude an important part of military action and would introduce a problematic ambiguity.

81 An example is provided by the already existing medical intestine camera that is swallowed and transmits its video images only over about 1 m distance.

82 Use for espionage is of course illegal everywhere; the proposed ban will not be able to stop such covert use by intelligence services, but widespread application by armed forces can probably be prevented.

Because the lower size limit of centimetres is clearly macroscopic, verification could rely on on-site inspections and close visual observation of equipment to a large extent. Inspections would be directed to military installations, training and testing grounds, as well as to institutes and firms where development could take place.

5.2 New Conventional Weapons

Among potential new conventional weapons, the picture is varied. Metal-less small arms and light weapons would pose strong dangers if they diffused to civilian society. Clear military advantages are not obvious, arguments in favour of civilian uses do not come to mind. This suggests a complete ban on small arms, light weapons and munitions that contain no metal. Should urgent reasons arise to develop such weapons and munitions, then producers should be obliged to include metallic patterns that immediately show up on x-ray and induction detectors. As long as small arms do not get smaller than about 10 cm and munitions about 1 cm, verification can rely on on-site inspections in military and security-force installations, testing and training grounds and production facilities. Visual observation should suffice, optimally supported by notification of types of arms and munitions and by individual markings on the arms.

Limits on small guidance and navigation systems would be extremely difficult to verify, because they concern mechanisms internal to the weapon/munition. To the extent that guidance/navigation systems contribute to a decrease in stability, it is probably more sensible to focus limits on the weapons or munitions containing them. In particular the problem of conventional attack against nuclear weapons and strategic command-and-control systems should be addressed.

Small missiles could destabilise the military situation if they will be capable of precisely hitting sensitive points of strategic importance. More dangerous could be their use against persons by terrorists in civilian society. Compared to existing portable air-defence missiles and artillery rockets of 1.5 m length, small missiles below 0.5 m size would form a new class of its own, all the more anti-personnel missiles below 5 cm size. Civilian uses are limited to the already existing fireworks and life-saving apparatus for shooting a lifeline to a stranded ship. As a consequence, a complete ban on missiles below a certain size limit (0.2-0.5 m) is recommended, with the exceptions mentioned. Verification is possible by visual observation during on-site inspections in installations of the military and security forces, including testing and training grounds, and in production facilities.

5.3 Implanted Systems/Body Manipulation

One class of future NT-enabled implants would monitor the biochemistry and release therapeutic drugs as required, e.g. sense the blood-sugar level in diabetes patients with immediate release of the correct amounts of insulin. Another class makes contact to nerves or the brain, picking up signals or stimulating muscles, nerves or the brain. Use in cochlear prostheses, for treating epilepsy or Parkinson's disease, or for restoring motion in paralysed patients, is not controversial. Medically motivated R&D for such purposes, and the eventual application, should of course not at all be hampered by efforts to prevent certain military uses of implants.

However, even in the civilian sector problems would arise when drug-releasing or nerve-/brain-contact implants would be used for improving the human, when artificial organs would provide better capabilities than the natural ones. Similarly to the handling of the issues of genetic manipulation and improvement of humans, society should carry out a thorough debate about limits to body manipulation and enhancement.

This debate will require considerable time; it should not be undermined by developments in the armed forces. The main goal is to provide time for society to arrive at a sound general decision, thus it seems best to introduce a moratorium on implants and other body manipulation that are not directly medically motivated. The moratorium should comprise the civilian and military sectors and last for 10 years, with the possibility of prolongation. It should be agreed upon by international understanding, involving bodies responsible for international co-ordination in the medical field such as the World Health Organisation (WHO). Should verification of compliance be deemed necessary, the WHO might conceivably play a role. For challenge inspections access to medical facilities, surgery records etc. together with rights to interview medical personnel as well as people who might have been subject to implant surgery or other body manipulation would be needed.

5.4 Armed Autonomous Systems

Armed robotic systems that would move on the ground, on or under water, or in the air need yet to be studied systematically under the aspects of preventive arms control. The problems they pose are mostly independent of NT, but NT-based computing power will be needed to achieve the required autonomy. NT can also come in with many types of sensors and actuators. This section presents first considerations on limiting options.[83]

There are practically no civilian uses of armed robots. One conceivable exception might be robots substituting human guards in securing closed facilities against intruders. Here small arms or non-lethal weapons would suffice, but these could already raise objections under constitutional criteria. Another exception would be robots used by the police to fight against hostage-takers. If accepted at all, such robots should be equipped only with arms similar to those of the police, and the mobility and number should be limited. Thus, they would be impractical for military combat and would not create ambiguity. The already existing remotely controlled robots for manipulating and shooting at suspected bomb briefcases fulfil these conditions well.

The military have considerable interest in armed autonomous systems – the combat efficiency would be higher due to higher agility and smaller size; fewer soldiers would be injured and killed; operations might be cheaper. However, these views are secondary considering the generally negative evaluation under the preventive-arms-control criteria in Section 4.3. Because armed autonomous systems would present a clear qualitative step, a general prohibition of re-usable armed, mobile systems without crew is possible and probably represents the best solution.[84] Most armed forces have not yet introduced such systems; the USA would have to remove the option of mounting a Hellfire missile on its Predator drones.

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[83] Some of this has been discussed by J. Altmann: Roboter für den Krieg? In: Wissenschaft und Frieden 21 (2003), 3, pp. 18-21.

[84] The wording 'without crew' instead of 'autonomous' has been chosen to include remotely controlled systems. Even though these are not autonomous in the proper sense of the word, they could be deployed in high numbers and later relatively simply and covertly changed to autonomous operation. Also, verification of autonomy versus remote control would be very difficult from outside.

Cruise missiles are already introduced with many armed forces. In one sense, they are an armed system that autonomously approaches a target and attacks it. In another sense, one could argue that a cruise missile follows a pre-planned course to a target and explodes there (one-time use), similarly to a ballistic missile or an artillery grenade. While there are reasons to argue for a ban on (certain types of) cruise missiles,[85] they are different enough from the systems discussed here that one should not burden the prohibition of new systems with the demand to withdraw and dismantle others that are already widely introduced.[86]

With a ban on armed systems, robots without weapons must not create opportunities for circumvention. For many autonomous systems of sizes from 1 m (ground, air) to 100 m and more (sea) one could already discern weapons or provisions for weapons by external observation from some distance. New unarmed systems such as a ground-mobile robot for demining or rescue of injured soldiers should be designed clearly without weapons function. However, such systems will often be modular, so that a manipulator, e.g., could later be exchanged by a firearm. Here numerical limits and rules of warfare[87] could help.

Extending the ban to include all autonomous military systems would remove the ambiguities about unarmed systems. However, the first robot lawnmowers and vacuum cleaners are already on the market, and the use of service robots of different kinds in civilian life is expected to increase strongly over the coming years. Under such circumstances it would be unrealistic to exclude military use of similar systems for e.g. logistics and transport. Robot control of weapons, on the other hand, crosses an obvious threshold.[88]

For answering the question of limits on unarmed robotic systems, one can look at the Treaty on Conventional Forces in Europe (CFE Treaty) of 1990.[89] In order to achieve ‘a secure and stable balance’ and to eliminate ‘the capability for launching surprise attack and for initiating large-scale offensive action in Europe’, the Treaty limits main weapons in five categories[90] and regulates equipment in six categories[91]. Transport lorries or transport aircraft are not limited. Pursuing and extending this logic, robotic systems clearly without combat function, such as robotic lorries or pilot-less transport aircraft might be left unregulated. However, in order to reduce the potential for arming them, numerical limits seem advisable also here.

It may turn out that a comprehensive prohibition of armed autonomous systems will not be politically feasible. In such a case, the least one should demand is preserving the CFE Treaty. Its definitions of the armaments do not mention crews. Robotic vehicles similar to the traditional ones would immediately fall under these definitions, and would thus count

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85 E.g. the prohibition on land-based cruise missiles above 500 km range of the INF Treaty of 1987 applies only to the USA and Russia – all other countries are free in this respect.

86 The proposed term ‘re-usable’ also excludes target-seeking sub-munitions for which similar arguments hold.

87 As with medical vehicles under Additional Protocol I to the Geneva Conventions of 1949.

88 This was also recognised by a military author, S. Metz: The Next Twist of the RMA. In: Parameters 30 (2000), 3, pp. 40–53. In: http://carlisle-www.army.mil/usawc/parameters/00autumn/metz.htm (13 Dec. 2002).

89 Amended and updated 1992 and 1996.

90 Battle tanks, armoured combat vehicles, artillery, combat aircraft and attack helicopters.

91 Primary trainer aircraft, unarmed trainer aircraft, unarmed transport helicopters, armoured vehicle launched bridges, armoured personnel carrier look-alikes and armoured infantry fighting vehicle look-alikes.

against the Treaty limits.[92] Potential new types of vehicles/robots could be outside of treaty definitions, such as a battle tank below 16.5 metric tons equipped with an electro-magnetic gun of less than 75 mm calibre, or person-size walking combat robots. To close such loopholes, additional categories with appropriate limits will be needed.

If autonomous combat vehicles cannot be prevented in general, crewless carriers could also be used for nuclear weapons (bombers, maybe also submarines, land-mobile inter-continental ballistic missiles or artillery). The least one should demand in such a case is that no qualitatively new types of nuclear-weapon carriers be introduced, e.g. a walking robot carrying a bomb. Reasons of safety and security will anyway argue for continuing direct human control of nuclear weapons.

Assuming that autonomous combat systems could not be prevented, the question arises whether autonomy should include the decision to direct and use a weapon against a specific target. Because autonomy in general brings destabilisation and because at least the first generations could not guarantee compliance with the international humanitarian law, the weapon targeting and release decision should remain in human hands, that is, it should only be done using remote control.[93]

Neither the proposed strong prohibition nor the mentioned weaker solution would restrict development and use of general-purpose robots in the civilian sector, so that here no balancing of benefits and costs is needed. The only exception would be armed systems for law-enforcement purposes – in order to prevent military build-up in the guise of police systems, some restraint will be needed.

Verification of the proposed ban on crewless armed, mobile systems could be based on external observation during on-site inspections and manoeuvre observations, based on regular data exchanges. Due to the size of these systems, weapons, weapons pods etc. could easily be discerned from the outside at short distance (a few metres). For the same reason, national technical means of verification could play a significant role for those who own them. Data exchanges and inspection rights should extend to development projects and testing areas.

Verification of the ban on autonomous weapon release and the obligation to use remote control by a human operator is practically not feasible, because the software governing release could be easily modified (verification of embedded software would be prohibitively intrusive anyway). This is no strong obstacle, however, because most rules of the international law of warfare cannot be verified in advance. They rather form norms for behaviour that can be evaluated after the action.

5.5 Mini-/Micro-Robots

While some considerations of the preceding section apply also to small robots, the latter pose additional problems: they could be used in very large numbers and they could be

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92 E.g. heavy armament combat vehicle: ≥ 6.0 metric tonnes, gun ≥ 75 millimetres.

93 Such a rule would be difficult to be upheld in an environment full of crewless systems mutually observing and threatening each other. This is another argument for strict numerical limits, including small systems.

easily hidden or would even be invisible. Because small robots (including bio-technical hybrids) with and without weapons function would bring strong dangers under military as well as civilian viewpoints, they should be prevented as completely as possible, taking into account indispensable positive uses. Small robots would represent qualitatively new systems, thus preventive limitation is possible.

For a clear definition and in the interest of verification, neither details of the inner working (such as NT-based control computers, sensors or actuators) nor the degree of autonomy nor the presence of a weapon mechanism should be considered. Simple characteristics visible from the outside are mobility and size. Very small systems would need examination under some type of microscope. Crewless weapons and systems that are introduced already with the armed forces are above 1 metre size: on land, there are at most prototypes of robots, in water, torpedoes and a few deep-diving robots, in the air, cruise missiles and uninhabited aerial vehicles/drones. To avoid demanding removal of existing armaments, a lower size limit below 1 m is advisable, somewhere between 0.5 and 0.2 m. This would be far enough above microscopic size that observation by eye would normally suffice during inspections.

The military interests in small robots for combat support and actual combat might turn out less than expected due to their limits in speed, range and payload. In any case, the dangers far outweigh the military advantages. Surveillance from the air, for example, can more effectively be done using larger craft, such as the existing uninhabited aerial vehicles. Mine detection and removal as well as rescue of injured soldiers could also be carried out better with systems above 0.5 or even 1 m size: the payload and range would be higher.

Mini-/micro-robots could be used beneficially in civilian society.[94] For several potential uses on/in land, water or air, however, systems above 0.5 or 1 m size would be suited better.[95] For other applications, fixed sensors could do the job.[96]

In law enforcement, applications for covert search for contraband, covert monitoring of hostage situations or for monitoring of criminal suspects may seem justified, but raise significant problems with privacy and human rights, in particular if the mini-/micro-robots are smaller than 1 mm and are produced in high numbers. Here, prevention of misuse will demand either a total renunciation or very strict qualitative and quantitative limits.

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94 See also J. Altmann: Military Applications of Microsystem Technologies – Dangers and Preventive Arms Control. Münster: agenda 2001 (Section 7.2 and refs).

95 E.g. remote characterisation of disaster areas, monitoring of pollutants, replacing weather balloons, tracking populations of endangered species.

96 E.g. monitoring of traffic, finding activity connected with illegal border crossing.

Among the remaining conceivable civilian applications there are only very few where mini-/micro-robots below 0.2 or 0.5 m size could not be replaced by larger ones:

- exploration of the moon, planets and asteroids,
- exploration of shattered or dangerous buildings,
- inspection of narrow pipes,
- surgical robots for movement and operations in the body,
- toys and amateur objects.

The first two categories could be handled by exceptions with numerical limits. For pipe inspection and surgical robots, neither general mobility nor autonomy is needed; misuse of robots made for this purpose could be prevented by restricting their capabilities. Fully capable small robots used as toys or amateur objects would bring a great potential for accidents and abuse. Thus, toy and amateur robots should be clearly limited – in mobility, sensing/actuating capability or autonomy. To hamper certain covert uses, they should not be produced below about 20 cm size.[97] Amateurs should not be allowed to use robots capable of moving outside of their homes or laboratories that are smaller than 0.2 or 0.5 m size.[98]

As a consequence, one arrives at a general prohibition of small mobile (partly) artificial systems below a certain size limit (0.2 to 0.5 m) in all media, in the military and the civilian sector, independent of the degree of autonomy and the biological-technical mix. Exceptions should be strictly defined and narrowly limited, as discussed above.[99]

Verification of compliance with the general prohibition and the exceptions can to a large extent rely on on-site inspections in military installations and training grounds, research, development and testing institutions. Visual close inspection of equipment and observation of its use will largely suffice as long as robot systems below about 1 mm will not be practical. To provide a chance for their detection already from the beginning, portable microscopes (at least optical, maybe also of the scanning-probe type) should be allowed during inspections.

Because nearly all exceptions are foreseen in the civilian sector, inspection rights are required here as well, mainly directed to industry, but also to law-enforcement agencies. To make sure that illegal manipulations of insects and other small animals can be detected, there needs to be a right to inspections of biological laboratories. Observation of public life and evaluation of public media will strengthen the verification effectiveness.

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97 Existing robotic ‘pets’ and dolls are in this category; the toy industry will probably not massively oppose such limitations that society would introduce to protect higher values.

98 Except for medical surgery as a temporary action, there seems to be no important civilian application of robots below 1 mm size for the next two decades. Micro- and nano-robots to stay in the body would pose different problems; molecule-size systems used as military weapons are banned by the Chemical Weapons Convention (see Section 5.7). Civilian application would need extremely strict rules to prevent abuse. Because this is still hypothetical, no specific limits are considered here.

99 Against circumvention by the exceptions technical limitations as well as licensing should be used, taking into account: reduced autonomy, reduced range, limit on speed, lower limit on size, external power supply, purpose, organisation, maximum number.

5.6 Small Satellites and Launchers

Small satellites would bring dangers due to their possible use as space weapons. Banning satellites smaller than a certain size would exclude that option, but would prevent positive uses of small satellites, and would not restrict larger space weapons. The best solution would be a comprehensive ban on space weapons of all kinds, including development and testing. This would allow all kinds of civilian small satellites, and military ones for non-weapons purposes. The risk of their misuse for anti-satellite attacks could be minimised by strict numerical limits, a licensing and inspection process and rules of the road that forbid close approach to other than one's own satellites.[100]

Verification could to a very large part rely on space observation from earth by radar and optical cameras, optimally augmented by pre-launch inspection after notification; space-to-space observation would add some capability.

5.7 New Chemical and Biological Weapons

New chemical or biological weapons enabled by NT would clearly violate the Chemical Weapons Convention (CWC) or the Biological and Toxin Weapons Convention (BTWC). Insofar as there are practically no such weapons known at present, new types would represent a qualitative step. The recommended option thus is to uphold both Conventions and reinforce their universal scope.

For the CWC, the definition of a 'toxic chemical' in Art. II (2) speaks of 'chemical action on life processes'. Some doubts could arise whether this comprises NT-based supramolecular systems such as nano-machines that would e.g. act mechanically, electrically or thermally on cell components. To avoid undermining the CWC, a clarifying interpretation would be needed, e.g. stating that all interactions of agents smaller than cells count as chemical.[101]

The verification means and methods that the CWC contains in its Annex on Implementation and Verification – declarations, inspections, equipment, seals, sensors, sample-handling, facility agreements etc. – seem to be sufficient for new agents.

Also the BTWC uses the general-purpose criterion in Art. I (1). Doubts may arise with respect to biological-technical hybrid organisms, 'artificial microbes' and nano-machines that are clearly non-biological. To prevent endangering the Convention, at least an additional clarification/interpretation would be needed; one solution could be to state that the Convention covers also hybrid and artificial systems that could enter an organism.[102]

The main weakness of the BTWC is the lack of verification; this problem has been recognised for a long time and becomes ever more urgent in the light of biotechnological advances. NT will accelerate such advances. The work on a compliance and verification

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[100] Small space launchers should be included in the regulation; they should only be allowed for legitimate small satellites.
[101] Such an interpretation could be concluded at the next Review Conference in 2008.
[102] A clarifying interpretation could be agreed upon at the next Review Conference in 2006.

protocol started more than a decade ago, but has been stopped in 2001.[103] In order to strengthen the BTWC, a new process towards a compliance and verification protocol should be started and brought to a fast conclusion. The existing rolling text with its provisions for challenge inspections in pharmaceutical laboratories, managed access, sample-taking etc.[104] has been designed with present biotechnology in mind, but could probably apply to NT-based further advances.

As in other areas, fastest progress in biotechnology is expected in civilian R&D and industry. This opens many possibilities for misuse, including exploitation of differences in national legislation. To minimise the risks, states should conclude a Biosecurity Convention that should be co-ordinated closely with the BTWC and its future verification and compliance mechanism.[105]

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103 K. Nixdorff/M. Hotz/D. Schilling/M. Dando: Biotechnology and the Biological Weapons Convention. Münster: agenda 2003 (Chs 8-11 and refs).

104 Rolling Text of a Protocol to the Convention on the Prohibition of the Development, Production and Stockpiling of Bacteriological (Biological) and Toxin Weapons and on their Destruction. Geneva, 18 May 2001. BWC/Ad Hoc Group/56-1, Appendices, .../56-2. In: http://www.brad.ac.uk/acad/sbtwc/doc56-1.pdf, .../doc56-2.pdf (9 Febr. 2004).

105 See e.g. Biosafety, Biosecurity, and Bioweapons – Three Agreements on Biotechnology, Health, and the Environment, and Their Potential Contribution to Biological Weapons Control. Background Paper #11. The Sunshine Project (October 2003). In: http://www.sunshine-project.org/publications/bk/bk11.html (27 Oct. 2003). J.B. Tucker: Preventing the Misuse of Pathogens: The Need for Global Biosecurity Standards. In: Arms Control Today 33 (2003), 5, pp. 3-10.

6 Recommendations and Conclusions

6.1 Recommendations[106]

The discussion of limitation options has led to the following recommendations for preventive arms control:

Distributed sensors

- Complete ban on self-contained sensor systems that are smaller than a certain size limit (3 to 5 cm), for the military and civilian sector, starting at the development stage, potentially with exceptions for important civilian applications of smaller sensor systems.
  Verification would rely mainly on on-site inspections with magnifying equipment.

New conventional weapons

- Uphold the Treaty on Conventional Armed Forces in Europe (CFE Treaty), adapt its definitions of treaty-limited equipment if new weapons and carriers with different parameters arrive. Introduce regulation similar to the CFE Treaty in the other regions of the world.
- Complete ban on small arms, light weapons and munitions that contain no metal, for the military and civilian sector, starting at the development stage. If weapons and munitions based on non-metallic materials were needed urgently, metallic patterns should be built in obligatorily for a clear signature on x-ray and metal detectors.
  Verification can mainly use on-site inspections with auxiliary equipment.
- Complete ban on missiles below a certain size limit (0.2 - 0.5 m), for the military and civilian sector, starting at the development stage, with exceptions for innocent civilian applications such as fireworks and life-saving apparatus for stranded ships.
  Verification can rely mainly on on-site inspections with auxiliary equipment.

Body manipulation

- Moratorium on body implants and other body manipulation that are not directly medically motivated. The moratorium should comprise the civilian and military sectors, start at the development stage and last for 10 years, with the possibility of prolongation. Concrete interpretations on what constitutes illegal/unethical body manipulation should be developed by international understanding.

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[106] For recommendations concerning further research, see Altmann, 2006, loc. cit. (note 23), Section 7.3.

Autonomous systems, normal size (above 0.2 - 0.5 m)

- General prohibition of re-usable armed, mobile systems without crew.
- Numerical limits on unarmed, mobile systems without crew, differentiated according to function.
- Prohibition of unarmed, mobile systems without crew in public areas and air space.
- If armed crewless systems cannot be prevented:
    - count them under the CFE Treaty (and potential future similar treaties for other regions);
    - if new systems fall outside of treaty definitions, adapt the latter and agree on numerical limits that strengthen the purpose of the Treaty.
    - No aiming and weapon release without human decision.
    - Prohibition of qualitatively new types of nuclear-weapon carriers.

All these prohibitions should apply to the military sector and start at the development stage.
Verification can rely mainly on on-site inspections.

Small mobile systems (size below 0.2 - 0.5 m)

- General prohibition of small mobile (partly) artificial systems below a certain size limit (0.2-0.5 m) on/in the ground, on/under water, in the air, independent of the degree of autonomy and the biological-technical mix, for the military and the civilian sector, starting at the development stage. For important positive applications there should be strictly defined and narrowly limited exceptions:
- in the civilian sector:
    - for exploration of celestial bodies,
    - for exploration of shattered or dangerous buildings,
    - for inspection of narrow pipes
    - for surgical operations;
- in the military sector:
    - for surgical operations.

For the exceptions, a combination of various technical measures and licensing procedures should prevent abuse.
Verification can rely mainly on on-site inspections with magnifying equipment.

Small satellites and launchers

- Comprehensive ban on space weapons of all kinds, starting at the development stage.
  Verification can to a large part rely on space observation from earth, augmented by pre-launch inspection after notification.
- Regulation, notification and inspection of small satellites and small launchers.

New chemical or biological weapons

- Uphold the Chemical Weapons Convention (CWC), conclude a clarifying interpretation that for (NT-enabled) agents that are smaller than cells and damage life processes within cells any kind of damaging action counts as 'chemical action' under Article 2.
- Uphold the Biological and Toxin Weapons Convention (BTWC), conclude a clarifying interpretation that (NT-enabled) microscopic systems that can enter the body and are partly or fully artificial are included.
- Conclude a Protocol on compliance and verification measures for the BTWC.
- Conclude a Biosecurity Convention, with close co-ordination to the BTWC and the new protocol.

In those areas where international agreement may turn out difficult to achieve, or negotiations may proceed only very slowly, export controls should be agreed between the states active in NT research and development (R&D), with the goal to contain proliferation of dangerous NT-based systems and applications.

Before, during and after conclusion of limitation agreements, transparency and confidence-building measures are very important in order to reduce mistrust. Mistrust is particularly worrisome in the area of NT where revolutionary changes are foreseen and rapid acceleration of developments is possible. It is positive that various national NT initiatives have included societal implications into their agendas. In the international dialogue on responsible research and development of NT, military applications should not be overlooked, but actively included, since some of the most problematic risks could come about by military R&D. Codes of conduct for NT should contain rules not only for civilian, but also for military R&D.

6.2 Concluding Thoughts

6.2.1 Military NT Needed for International Peace Operations?

In principle, considerations about international security and peace could lead to the requirement that armed forces carrying out international peace operations or humanitarian interventions – under a UN mandate – should have all kinds of military NT applications available in order to apply force, if needed, as efficiently and selectively as possible. Independent of the general discussion about the justification of such operations, it seems that the narrow scope of preventive limitation recommended here would not much restrain military efficiency in these circumstances.

Of course, the systems falling under the proposed prohibitions could all add to the fighting capability of peace forces. However, the marginal increase in their efficiency would in no way balance the general dangers of arms race, destabilisation, proliferation, terrorist use etc. connected to wide-spread introduction of such systems.

6.2.2 Central Role of the USA

The military policy of the USA – the remaining sole superpower – in general aims at technological superiority and global dominance in armed conflict.[107] The present administration has strengthened this trend and emphasised unilateral military action, downplaying multilateral agreement including arms limitation.

In particular in military R&D of NT, the USA is outspending the combined rest of the world by a factor from 4 to 10 (see Section 2.3). As in many other technology areas, also in NT the USA is probably engaged in a virtual arms race with itself. Thus, unilateral restraint by the USA in the most problematic military NT applications would for a considerable time not result in technological threats from others. Of course, for enduring security from such threats, legally binding multilateral limitation agreements with appropriate verification will be needed. Unilateral restraint by the technology leader could buy sufficient time to work out just these agreements. Leaving military NT applications unrestricted would probably mean that will find their ways into the hands of potential opponents – states or non-state actors – by many routes: exports, technology transfer, other arms developers following the US example. In turn, these applications would create increasing threats to the USA.

There is a certain tradition in the USA of restraint and agreed limitation in new military technologies, as demonstrated by the Antiballistic Missile Treaty (1972-2002) and the Laser Blinding Weapons Protocol (1995). The former was conditioned on the Cold War with an ideologically antagonistic superpower as a potential opponent. This situation has changed, but at the fundamental level, military threats still form important parts of national security, not only between the USA, Russia and China.

With NT, revolutionary new military applications are on the horizon that without doubt will be accessible to many actors – Russia and China among them – though with some delay. Metal-free firearms, autonomous micro-robots, selective chemical agents etc. – could all lead to very disturbing threats to the security of the USA, posed by military opponents, agents or terrorists. Thus, a hard look at future security in the framework not of narrow military advantage, but of enlightened national interest could well lead to the insight that international limitations of the most dangerous NT applications would be advantageous for the USA.

As long as the USA is not receptive to such arguments, it may nevertheless be useful for the rest of the international community to prepare, and maybe even conclude, limitation treaties.[108]

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107 See e.g. Joint Vision 2020. General Henry H. Shelton, Chairman of the Joint Chiefs of Staff. Washington DC: Government Printing Office 2000.

108 Even if without the USA other important actors do not become parties, such agreements would create obligations for relevant countries and will have some political effect inside the USA. The situation with the Anti-personnel Mine Convention of 1997 is somewhat similar.

6.2.3 Further Development of the International System?

NT together with the other ‘converging’ technologies that it will enable – biotechnology with genetic engineering and manipulation of cell mechanisms, information technology with ubiquitous small computers, new levels of artificial intelligence and large and small robots etc. – will create not only ethical challenges, but many possibilities for misuse. Pervasive and often very small, these technologies will be difficult to control. Within civil societies, the general mechanisms of democratic decision, legislation, licensing, inspection and criminal prosecution may be sufficient to guarantee security for the members and institutions of society.

In order to ensure – and sometimes enforce – compliance with the rules, civilian societies have come to accept some relatively strict limits and fairly wide-ranging rights for inspection by state personnel – e.g. in the areas of work safety, environment, correct accounting and criminal investigation. For small and pervasive systems, similar degrees of inspection would be required on the international level to verify compliance with agreed limits. This is conceivable in the civilian sector – but even here the fear of invading into commercial secrets will create problems. In the military sector, on the other hand, limitations as such as well as intense inspection will meet strong resistance, since exploitation of new technology as well as secrecy are essential parts of preparations for armed conflict.

As a consequence, one arrives at the problem that the traditional way of guaranteeing national security – namely by the threat of armed force – may be no longer compatible with the advance of technology. If the security threats following from new technology can only be contained by intense inspections that would endanger the very functioning of the armed forces in their central role, security can no longer be reliably ensured by national armed forces.

In this vein, the powerful new technologies that require stringent international control could act as a catalyst in a process of moving away from the security dilemma and strengthening civilian-society elements in the international system. This would mean strengthened international institutions and international law, in particular criminal law with prosecution of perpetrators, moving into a direction towards an international monopoly of legitimate force, strong enough to prevent or punish threats or use of illegal force. In such a process, reliance on national armed forces for security could be reduced step by step.

Bibliography

Altmann, J.: Military Applications of Microsystem Technologies – Dangers and Preventive Arms Control. Münster: agenda 2001.

Altmann, J.: Roboter für den Krieg? In: Wissenschaft und Frieden 21 (2003), 3, pp. 18-21.

Altmann, J.: Military Uses of Nanotechnology: Perspectives and Concerns. In: Security Dialogue 35 (2004), 1, pp. 61-79.

Altmann, J.: Military Nanotechnology: Potential Applications and Preventive Arms Control. London/New York: Routledge 2006.

Altmann, J./Gubrud, M.: Risks from Military Uses of Nanotechnology – the Need for Technology Assessment and Preventive Control. In: M. Roco, R. Tomellini (eds.): Nanotechnology – Revolutionary Opportunities and Societal Implications. Luxembourg: European Communities 2002. In: http://www.ep3.ruhr-uni-bochum.de/bvp/riskmilnt_lecce.html (30 April 2004).

Andrievski, R.A.: Modern nanoparticle research in Russia. In: Journal of Nanoparticle Research 5 (2003), 5-6, pp. 415–418.

Army selects MIT for $50 million institute. MIT News, March 13, 2002, updated March 14, 2002. In: http://web.mit.edu/newsoffice/nr/2002/isn.html (15 March 2002).

Army Teams with MIT to Establish ISN. U.S. Army News Release, March 13, 2002. In: http://www.dtic.mil/armylink/news/Mar2002/r20020313r-02-011.html (15 March 2002).

Arnett, E.: Military research and development. In: SIPRI-Yearbook 1999 – World Armaments and Disarmament. Stockholm/Oxford: SIPRI/Oxford University Press 1999.

Bai, C.: Progress of nanoscience and nanotechnology in China. In: Journal of Nanoparticle Research 3 (2001), 4, pp. 251-256.

Bhushan, B. (ed.): Springer Handbook of Nanotechnology, Berlin etc.: Springer 2004.

Biosafety, Biosecurity, and Bioweapons – Three Agreements on Biotechnology, Health, and the Environment, and Their Potential Contribution to Biological Weapons Control. Background Paper #11. The Sunshine Project (October 2003). In: http://www.sunshine-project.org/publications/bk/bk11.html (27 Oct. 2003).

BMBF: Nanotechnologie in Deutschland – Standortbestimmung, Bonn: Bundesministerium für Bildung und Forschung 2002.

Bonn International Center for Conversion: conversion survey 2001 – Global Disarmament, Demilitarization and Demobilization. Baden-Baden: Nomos 2001.

Burgess, D.E.: UK MoD's nanotechnology initiatives. Viewgraphs presented at Defence Nanotechnology 2002, 31 Oct.-1 Nov. London: Defence Event Management 2002.

Center for Integrated Nanotechnologies. 2003. In: http://cint.lanl.gov (27 Jan. 2003).

Controlled Biological and Biomimetic Systems. 2003. In: http://www.darpa.mil/dso/thrust/biosci/cbs.htm, .../biosci/cbs/overview.html, .../biosci/cbs/cprogram.html (13 Feb. 2004).

Devine, M.: Manufacturing, Research, Development, and Education (RDE) Center for Nanotechnologies. Viewgraphs presented at Defence Nanotechnology 2002, 31 Oct.-1 Nov. London: Defence Event Management 2002.
Drexler, K.E.: Molecular engineering: An approach to the development of general capabilities for molecular manipulation. In: Proceedings of the National Academy of Sciences 78 (1981) 9, pp. 5275-5278.
Drexler, K.E.: Engines of Creation – The Coming Era of Nanotechnology. New York: Anchor/Doubleday 1986/1990.
Drexler, K.E. et al.: On Physics, Fundamentals, and Nanorobots: A Rebuttal to Smalley's Assertion ... Foresight Update no. 46 (30 Sept. 2001), pp. 6-7. In: http://www.imm.org/SciAmDebate2/smalley.html (4 Nov. 2003).
Drexler, K.E. et al.: Many Future Nanomachines: A Rebuttal to Whiteside's Assertion ... Foresight Update no. 46 (30 Sept. 2001), pp. 8-17. In: http://www.imm.org/SciAmDebate2/whitesides.html (4 Nov. 2003).
Drexler, K.E./Smalley, R.E.: Nanotechnology – Drexler and Smalley make the case for and against “molecular assemblers”. In: Chemical & Engineering News 82 (2003), 48, pp. 37-42.
Executive Summary. 2001. In: http://www.nanoisrael.netfirms.com/executive_summary.htm> (accessed 26 Sept. 2003).
Feynman, R.: There’s Plenty of Room at the Bottom: An Invitation to Enter a New Field of Physics. Speech, 29 December 1959, American Physical Society Annual Meeting, California Institute of Technology. In: http://www.its.caltech.edu/~feynman (25 Aug. 2003).
Fiscal Year (FY) 2004/FY 2005 Biennial Budget Estimates, Febr. 2003, Research, Development, Test and Evaluation, Defense-Wide, Vol. 1. Defense Advanded Research Projects Agency. 2003. In: http://www.darpa.mil/body/pdf/FY04_FY05BiennialBudgetEstimatesFeb03.pdf (16 Febr. 2004)
Freitas, R.A.: Nanomedicine, Vol. I: Basic Capabilities. Georgetown TX: Landes Bioscience 1999.
Haberzettl, C.A.: Nanomedicine: destination or journey? In: Nanotechnology 13 (2002), 4, pp. R9-R13.
Hall, J.S.: Architectural considerations for self-replicating manufacturing systems. In: Nanotechnology 10 (1999), 3, pp. 323-330.
Holdridge, G.M. (ed.): Russian Research and Development Activities on Nanoparticles and Nanostructured Materials. Baltimore MD: International Technology Research Institute 1999. In: http://wtec.org/loyola/nano/Russia/nanorussia.pdf (25 April 2003).
Howard, C.V.: Nano-particles and Toxicity. In: No Small Matter II: The Case for a Global Moratorium – Size Matters! ETC Group Occas. Paper Series 7 (1) (2003). In: http://www.etcgroup.org/documents/Occ_Paper_Nanosafety.pdf (25 April 2003).
Howard, S.: Nanotechnology and Mass Destruction: The Need for an Inner Space Treaty. In: Disarmament Diplomacy, no. 65 (July-August 2002). In: http://www.acronym.org.uk/dd/dd65/65op1.htm (26 Aug. 2002).
Institute for Soldier Nanotechnologies: Mission and Overview. 2002. In: http://web.mit.edu/isn/overview.html (29 Oct. 2002).
Institute for Soldier Nanotechnologies: Research. 2002. In: http://web.mit.edu/isn/research/index.html (29 Oct. 2002).
Joint Vision 2020. General Henry H. Shelton, Chairman of the Joint Chiefs of Staff. Washington DC: Government Printing Office 2000.

Joy, B.: Why the future doesn't need us – Our most powerful 21st-century technologies – robotics, genetic engineering, and nanotech – are threatening to make humans an endangered species, Wired 8.04 (2000). In: http://www.wired.com/ wired/archive/8.04/joy_pr.html (16 Jan. 2003).

Kurzweil, R.: The Age of Spiritual Machines – When Computers Exceed Human Intelligence. New York etc.: Penguin 1999.

Leo, A.: The Soldier of Tomorrow – The U.S. Army enlists the Massachusetts Institute of Technology to build the uniform of the future. 2002. In: http://www. technologyreview.com/articles/leo032002.asp (8 April 2002).

McKendree, T.: The logical core architecture. In: Nanotechnology 9 (1998), 3, pp. 212-222.

Merkle, R.C.: A proposed "metabolism" for a hydrocarbon assembler. In: Nanotechnology 8 (1997), 4, pp. 149-162.

Merkle, R.C.: Molecular building blocks and development strategies for molecular nanotechnology. In: Nanotechnology 11 (2000), 2, pp. 89-99.

Metz, S.: The Next Twist of the RMA. In: Parameters 30 (2000), 3, pp. 40–53. In: http://carlisle-www.army.mil/usawc/parameters/00autumn/metz.htm (13 Dec. 2002).

Miasnikov, E.: Precision Guided Weapons and Strategic Balance (in Russian). Dolgoprudny: Center for Arms Control, Energy and Environmental Studies at MIPT 2000. In: http://www. armscontrol.ru/start/publications/vto1100.htm (18 April 2002).

Military Doctrine of the Russian Federation. Presidential Decree of April 21 2000. In: http://www.dcaf.ch/publications/e-publications/Rus_legal_acts/04_Military _doctrine.pdf (5 April 2004).

Minatec 2001. In: http://www.minatec.com/us/minatec.htm, .../minatec.pdf (18 Jan. 2001).

Moravec, H.: Mind Children – The Future of Robot and Human Intelligence. Cambridge MA/London: Harvard University Press 1988.

Moteff, J.D.: Defense Research: A Primer on the Department of Defense's Research, Development, Test and Evaluation (RDT&E) Program. CRS Report 97-316 (1999). In: http://www.NCSEonline.org/nle/crsreports/science/st-63.cmf (27 Nov. 2002).

Mullins, W.M.: Institute for Soldier Nanotechnologies. Viewgraphs presented at Defence Nanotechnology 2002, 31 Oct.-1 Nov. London: Defence Event Management 2002.

Murday, J.S.: Science and technology of nanostructures in the Department of Defense. In: Journal of Nanoparticle Research 1 (1999), 4, pp. 501-505.

Nanoscience & Nanotechnology at Sandia National Laboratories. 2003. In: http://nano.sandia.gov (27 Jan. 2003).

Nanotechnology holds a Key to Israel's Future. In: Jerusalem Post (6 March 2003). In: http://www.smalltimes.com/document_display.cfm?document_id=5613 (26 Sept. 2003).

Nanotechnology: Its Impact on Defence and the MoD. Nov. 2001. In: http://www.mod. uk/linked_files/nanotech.pdf, see also http://www.mod.uk/issues/ nanotech/contents.htm (18 Nov. 2003).

Nanotechnology Research Directions: IWGN Workshop Report. Washington DC: National Science and Technology Council Sept. 1999. In http://www.wtec. org/loyola/ nano/IWGN.Research.Directions/IWGN-rd.pdf (10 Sept. 2002).

National Nanotechnology Initiative – Research and Development Supporting the Next Industrial Revolution – Supplement to the President's FY 2004 Budget. Wash-

ington DC: National Science and Technology Council 2003. In: http://nano.gov/nni04_budget_supplement.pdf (17 Nov. 2003).
National Security Concept of the Russian Federation. Translation from Rossiiskaya Gazeta, January 18, 2000. In: http://www.fas.org/nuke/guide/russia/doctrine/gazeta012400.htm (5 April 2004).
Neuneck, G./Mölling, C.: Methoden, Kriterien und Konzepte für Präventive Rüstungskontrolle. In: Wissenschaft und Frieden, Dossier Nr. 38, 2001.
Nixdorff, K./Hotz, M./Schilling, D./Dando, M.: Biotechnology and the Biological Weapons Convention. Münster: agenda 2003.
Olds, J.: Self-Stimulation of the Brain. In: Science 127 (1958), 3294, pp. 315-324.
QinetiQ Nanomaterials – Ignitors. 2003. In: http://www.nano.qinetiq.com/03 _applications_knowledge/showcase.asp (18 Nov. 2003).
Reip, P.: Nanomaterials in Defence. Viewgraphs presented at Defence Nanotechnology 2002, 31 Oct.-1 Nov. London: Defence Event Management 2002.
Rolling Text of a Protocol to the Convention on the Prohibition of the Development, Production and Stockpiling of Bacteriological (Biological) and Toxin Weapons and on their Destruction. Geneva, 18 May 2001. BWC/Ad Hoc Group/56-1, Appendices, .../56-2. In: http://www.brad.ac.uk/acad/sbtwc/doc56-1.pdf, .../doc56-2.pdf (9 Febr. 2004).
Roman, C.: It's Ours to Lose – An Analysis of EU Nanotechnology Funding and the Sixth Framework Programme. Brussels: European Nanobusiness Association 2002. In: http://www.nanoeurope.org/docs/European%20Nanotech%20Funding.pdf (10 Nov. 2003).
Roco, M.C.: International strategy for nanotechnology research and development. In: Journal of Nanoparticle Research 3 (2001), 5-6, pp. 353-360.
Roco, M.C.: National Nanotechnology Investment in the FY 2003 Budget Request by the President. 2002. In: http://nano.gov/2003budget.html (10 Sept. 2002).
Roco, M.C.: Government Nanotechnology Funding: An International Outlook. NSF 2003. In: http://www.nano.gov/intpersp_roco_june30.htm (28 Oct. 2003).
Roco, M.C./Bainbridge, W.S. (eds): Societal Implications of Nanoscience and Nanotechnology. Boston etc.: Kluwer 2001. In: http://www.wtec.org/loyola/nano/societalimpact/nanosi.pdf (22 Sept. 2003).
Roco, M.C./Bainbridge, W.S. (eds.): Converging Technologies for Improving Human Performance – Nanotechnology, Biotechnology, Information Technology, and Cognitive Science. Boston, MA: Kluwer 2003 (also http://www.wtec.org/Converging Technologies).
Savage, S.J.: Evolution of a Swedish defence nanotechnology programme. Viewgraphs presented at Defence Nanotechnology 2002, 31 Oct.-1 Nov. London: Defence Event Management 2002.
Smalley, R.E.: Of Chemistry, Love and Nanobots. In: Scientific American 285 (2001), 3, pp. 76-77.
Talbot, D.: Supersoldiers. In: Technology Review (October 2002), pp. 44-51.
Tucker, J.B.: Preventing the Misuse of Pathogens: The Need for Global Biosecurity Standards. In: Arms Control Today 33 (2003), 5, pp. 3-10.
Tyler, P.E.: U.S. Strategy Plan Calls For Insuring No Rivals Develop. In: New York Times, 8 March 1992.
University of California, Riverside: New center for nanoscale innovation transfers knowledge from universities to industry. News Release, Dec. 10, 2002. In: http://www.newsroom.ucr.edu/cgi-bin/display.cgi?id=305 (3 Febr. 2003).
Wang, J./Dortmans, P.J.: A Review of Selected Nanotechnology Topics and Their Potential Military Applications. DSTO-TN-0537. Edinburgh South Australia: Systems

Sciences Laboratory, Defence Science and Technology Organisation 2004. In: http://www.dsto.defence.gov.au/corporate/reports/DSTO-TN-0537.pdf (30 April 2004).

Whitesides, G.M.: The Once and Future Nanomachine. In: Scientific American 285 (2001), 3, pp. 78-83.

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