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# Military Uses of Nanotechnology: Perspectives and Concerns

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It is predicted that nanotechnology (NT) will bring revolutionary changes in many areas, with the potential for both great benefits and great risks. Developments in the military could entail specific dangers, containment of which will need special analysis and effort. Military research and development in NT is expanding rapidly. Potential future applications span all areas of warfare. Special dangers to arms control and stability may arise from new biological weapons and microrobots. For humans and society, non-medical body implants – possibly made more acceptable via the military – raise a number of problems concerning human nature. Further research is needed to find the best way to avoid possible dangers. For the near and medium term, several guidelines for limits and restrictions are suggested. As a first step, transparency and international cooperation should be improved.

**Keywords** military • nanoscience • nanotechnology • preventive arms control • technology assessment

NANOTECHNOLOGY (NT) WILL BE THE BACKBONE of the next fundamental technology wave.[1] Science and technology have advanced to a point where structuring matter at the nanometre scale (1nm = $10^{-9}$m, a billionth of a metre) is becoming routine. Scanning-probe microscopes now allow us to image and move single atoms on a surface. In the life sciences, molecular processes within cells are being elucidated, microelectronics are being reduced to below 100nm, and the first cosmetics containing nanoparticles are already on the market. Increasingly powerful computers allow ever better modelling of matter at the atomic and molecular scale.

Expecting huge markets in the future, both governments and large and small enterprises have greatly increased their NT research and development

[1] NT (which here includes nanoscience) deals with structures from 0.1nm (atom) to 100nm (very large molecule) size.



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(R&D). In 2003, government spending alone represents $650–800 million in each of Western Europe, Japan, the USA and the rest of the industrialized countries (Roco, 2003). NT is predicted to produce revolutionary changes, bringing far-reaching consequences in many areas. Expected benefits include stronger, lighter and smart materials, computers that are smaller, consume less power and are far more powerful, diagnostics and therapy at the single-cell level, reduction of resource use and pollution, and miniaturized, highly automated space systems (see, for example, Roco & Bainbridge, 2001: 3–12). Some visions of NT reach farther: to artificial intelligence of human capability and beyond; robotics from nano to macro scale; nanodevices within the human body that eradicate illness and ageing or interface with the brain; and universal molecular assemblers capable of self-replication, leading to super-automated production.[2] Whether such visions can be realized has been disputed, particularly with regard to the assembler concept.[3] However, following the precautionary principle, one should take these possibilities seriously as long as they have not been demonstrated to be impossible for fundamental or technical reasons. Some were discussed at a recent workshop sponsored by the US government on improving human performance through the convergence of nano, bio, information and cognitive science and technology (NBIC) – for example, nano-implant devices, slowing down or reversing ageing, direct brain–machine interfaces and 'artificial people'.[4]

Yet, while opening up fundamentally new possibilities, NT also poses grave risks, among them environmental pollution, increased inequality, invasion of privacy, displacement of human workers and physical harm. Molecular NT would increase the risks even further – as consequences of automatic production, or through accidents or malevolent use of self-replicating systems, for example.[5] Debate on the general risks posed by NT has already begun. The US National Nanotechnology Initiative/National

[2] A universal molecular assembler would be a complex molecular system that would read a program of instructions, take the corresponding atoms or molecules from the surroundings and put them together to form the intended product, in a manner roughly similar to the processes in a living cell but not limited to biological conditions and materials. By varying the program, any structure compatible with the laws of nature could be synthesized, in particular a copy of the assembler itself. For macroscopic useful goods, many generations of self-replication would first produce billions of assemblers, which would then turn to making the intended product. This has been called 'molecular NT' by Drexler (1986); proponents expect that such technology will arrive within decades. In this article, the term 'molecular NT' is used in this sense. Of course, much present NT research deals with molecules but has nothing to do with assemblers.

[3] Refutations of the concept of molecular assemblers argue that they are (nearly) impossible by the laws of nature or will not arrive within a long time (Tolles, 2001; Smalley, 2001; Whitesides, 2001; for countering arguments, see Drexler et al., 2001a,b). Scientific articles in refereed journals are lacking. For peer-reviewed molecular-NT articles, on the other hand, see, for example, Merkle (2000) and references cited therein.

[4] Roco & Bainbridge (2002: 101ff., 179ff., 182ff., 213ff., 244ff., 251ff., 258).

[5] For a list of potential dangers, see CRN (2003).

Science Foundation and the European Commission have explicitly recognized the need to investigate the societal implications of NT (Roco & Bainbridge, 2001; Roco & Tomellini, 2002). However, there is a paucity of ethical, legal and social research (Mnyusiwalla, Daar & Singer, 2003). This is even more the case regarding risks from military uses of NT.

The aim of this article is to raise awareness of the dangers connected with military NT activities and to offer some preliminary recommendations.[6] After a brief overview of the literature, the article presents a summary of current military R&D on NT in the USA. It then discusses potential military uses of NT before turning, in the subsequent section, to the question of preventive arms control, which leads to a concluding discussion and recommendations. Aspects of molecular NT are discussed in separate paragraphs.

## Previous Writing on Military NT

Up until now, there has been practically no scholarly research on military NT. The topic has been discussed mainly in government papers, conferences, military journals and popular media.

Seen from a narrow national-security standpoint, NT provides grand new options for the military. For the year 2030 or after, the UK Ministry of Defence foresees nano-solar cells and nanorobots designed for a range of purposes – including medical robots used internally in humans and micro-platforms for reconnaissance (UK Ministry of Defence, 2001). The US National Nanotechnology Initiative (NNI) has referred to the possibility of information dominance through nanoelectronics; virtual reality systems for training; automation and robotics to offset reductions in manpower, reduce risks to troops and improve vehicle performance; higher-performance platforms with diminished failure rates and lower costs; improvements in chemical/biological/nuclear sensing and casualty care; improvements in systems for non-proliferation monitoring; and nano-/micromechanical devices for control of nuclear weapons (Roco & Bainbridge, 2001: 10–11). The national-security panel of the US NBIC workshop stated that in 'deterrence, intelligence gathering, and lethal combat . . . it is essential to be technologically as far ahead of potential opponents as possible' (Asher et al., 2002). Others have looked with a wider angle and have hinted at potential harmful

[6] This article expands an an earlier presentation (Altmann & Gubrud, 2002) and builds on my study of military applications of microsystems technology (MST) (Altmann, 2001). Dealing with structures of micrometre size (a thousand-fold larger than those of NT), MST is already established, though still advancing fast. MST and NT will mutually interact and accelerate each other. A larger study on NT is in preparation (Altmann, forthcoming).

uses of nanoweapons or the potential for controlled distribution of biological and nerve agents (ESANT, 1999; Meyer, 2001; Smith, 2001). Questions have been posed as to killing by robots (Metz, 2000; Crow & Sarewitz, 2001).[7] Some authors acknowledge that national security will have to be sought in a context of global security (Yonas & Picraux, 2001; Petersen & Egan, 2002). Aside from such hints, discussions of strategy and security have not yet taken up NT in a systematic fashion.

Dangers from military uses of *molecular* NT were already under discussion when the vision was first described to the general public (Drexler, 1986: 171–202). Destabilizing effects and arms races arising in particular from exponentially growing autonomous production were considered by Gubrud (1997). Joy's (2000) warnings about genetics, NT and robotics have become widely known, and have evoked much critical comment. However, this has been mainly directed at general aspects rather than the dangers posed by military/terrorist uses (e.g. Brown & Duguid, 2001; Tolles, 2001; Smith, 2001).

Moreover, the little arms-control discussion that exists has mostly addressed molecular NT. Drexler (1986: 171–202) argued in general terms for international agreements, but finally recommended 'active shields': nanomachines that, like the white blood cells of the human immune system, would 'fight dangerous replicators of all sorts'. However, the feasibility of such shields seems even more unclear than that of self-replicating systems themselves. Gubrud (1997) stated that not producing weaponry *en masse* would be verifiable, calling for a space weapons ban and recommending a single global security regime. The Foresight Guidelines (Foresight Institute, 2000), suggesting rules to prevent runaway replication, mention the risk of military abuse, but explicitly reject limitations by treaty because 'a 99.99% effective ban would result in development and deployment by the 0.01% that evaded and ignored the ban'. Truly 100% verifiability can of course never be achieved, but a strong verification regime could restrain the technological development of leading states that might otherwise be caught in an accelerating arms race. In order to prevent NT-enabled mass destruction, Howard (2002) has presented two alternative approaches: reserving 'inner (atomic and molecular) space' for peaceful exploitation, or preserving it as a 'sanctuary', forbidding nanotechnological exploration and engineering completely.[8]

[7] Note that one US military writer has stated that 'military systems (including weapons) [are] now on the horizon [that] will be too fast, too small, too numerous, and will create an environment too complex for humans to direct' (Adams, 2001).

[8] The author does not discuss historical research, existing applications and definitional problems. Modelling limitation treaties for the very small after the Outer Space Treaty is certainly inappropriate.

# Military R&D of NT in the USA

While other countries are certainly active in military R&D of NT, there can be little doubt that the USA is spending far more than any other country, and maybe more than the rest of the world combined.[9] Military R&D in the USA is much more transparent – not only in comparison to, for example, Russia or China, but also relative to countries such as the UK, France or Germany. Because US military NT activities provide an important precedent, they will be briefly described here.

US military R&D of NT started in the early 1980s with ultra-submicron electronics; later, scanning-probe microscopy became a focus; and in 1996, nanoscience was named one of six strategic research areas for defence.[10] Within the NNI, founded in 2000, 25–30% of the funding goes to the Department of Defense (DoD). Military NNI funds are spent by the R&D agencies of the DoD and the armed services.[11] Much work is done in the laboratories of the services themselves. Basic science and engineering in universities is supported by the Defense University Research Initiative in NT (DURINT). In 2001, 16 grants were awarded for work on nanoscale machines, carbon nanotubes, quantum computing, magnetic nanoparticles, etc. In addition, 17 grants were given for acquisition of NT research equipment (*DefenseLink*, 2001).

In March 2002, the US Army selected the Massachusetts Institute of Technology (MIT) to be the host for the Institute for Soldier Nanotechnologies (*MIT News*, 2002; Talbot, 2002).[12] Here, $50 million is to be spent during the first five years, plus an additional $40 million from industry. Up to 150 people will carry out basic and applied research in seven teams, focusing on materials and sensors for soldier protection (against bullets, directed energy, chemical/biological agents), performance enhancement, and body monitoring and injury intervention. One goal is to reduce the weight of infantry-soldier equipment from 60 to 20 kg. Another guiding vision is the development of a battle suit that dynamically provides protection, communication, mechanical enhancement and thermal management, compresses wounds and administers therapeutic drugs.

Broad national-security goals as guidelines for military R&D in the con-

[9] Figures on military NT R&D funding in other countries are difficult to obtain. The conjecture is supported by the following: the USA spends about two-thirds of the global military R&D expenditure at large (BICC, 2002); in the field of MST, according to a cautious estimate the US military R&D spending was more than ten times that of Western Europe (Altmann, 2001: 46); conference and internet presentations show an overwhelming preponderance of US work in military NT.

[10] Related expenses were $70 million in Fiscal Year (FY) 1999 (Murday, 1999).

[11] The DoD share of the NNI has grown from $70 million (of a total $270m) in FY 2000 to $243 million (of $774m) in FY 2003. Of the $201 million originally requested for FY 2003, $96 million were for basic research and $105m for applied research/advanced technology development (Roco, 2002a, 2003).

[12] Further information on the ISN is available at http://web.mit.edu/isn/index.html (24 November 2003).

vergence of NT, biotechnology, information technology and cognitive science were expressed at the NBIC workshop (Asher et al., 2002; see also CIEMN, 2002). These goals include the development of miniature sensors, high-speed processing, wide-bandwidth communication, unmanned combat vehicles, improved virtual-reality training, enhancement of human performance (e.g. modified biochemistry to compensate for sleep deprivation) and applications of a brain–machine interface.

While the military part of the NBIC workshop was more cautious than the other sections with respect to far-reaching concepts of human-body manipulation etc., the US military is open towards such ideas. For example, in 2001 an army workshop mentioned 'artificial systems within the soldier' such as 'neurofunctional implants', 'biological input/output devices', and 'implanted miniature computers'.[13] Whereas some of these concepts would have beneficial medical uses (e.g. in paralysed patients), their general application in soldiers would raise important ethical problems, with consequences already for the research stage.[14]

## Potential Military Uses of NT

A wide variety of military NT applications is conceivable as outcomes of R&D (not confined to the US guidelines mentioned above). In the following, several examples are given, excluding molecular NT (Altmann, forthcoming).

- *Electronics and computers* will become much smaller and at the same time much faster and less power-consuming through the use of NT. Such systems – augmented by new levels of *artificial intelligence* – will be used throughout the military, even embedded in very small components (rifles, glasses, uniforms, mini- and microrobots, munitions). On the other hand, large battle-management and strategy-planning systems will encompass many layers and a high degree of autonomous decision-making. Together with sensors, wireless communication components and small, lightweight displays, they would form an ubiquitous network not only on the battlefield, but also, for example, in logistics.

[13] This was characterized as a 'high-risk, visionary' programme (ARO, 2001). The workshop 'Nanotechnology for the Soldier' was part of the preparations for the founding of the Institute for Soldier Nanotechnologies.

[14] Note that the present Brain Machine Interface programme of the Defense Advanced Research Projects Agency (DARPA) intends to derive human–brain signals by non-invasive means (e.g. using multiple sensors on the scalp). However, magnetic particles in the brain are being discussed, and a university specializing in micro-electrode recording of animal brain activity is involved in the research (Wessberg et al., 2000; Nicolelis, 2001; Rudolph, 2001; Duke University, 2002; Nicolelis & Chapin, 2002; see also Hoag, 2003).

- NT allows smaller *sensors* – principally, down to sizes of micrometres instead of centimetres[15] – but in many cases signal strength depends on the size of the receiving component, potentially limiting the downsizing of the overall system. A lower-size limit can also derive from the communication antenna or the power supply. Nevertheless, cheap mass production may allow distribution of tens of thousands of sensors in a particular area.
- Lighter, stronger and more heat-resistant *materials* will provide higher speed and agility for conventional ground, water and air vehicles, but may also allow new types of smaller vehicles, all with more efficient engines. Lighter energy-storage and conversion systems – such as fuel cells using nanoparticle-based membranes or hydrogen tanks based on nanotubes or fullerenes – could make all-electric military vehicles practical, including electromagnetic guns. For small systems, contracting molecules or deforming materials offer the potential of muscle-like motion. Surfaces with locally variable colour – for example, through the use of mobile pigment particles – can be used for camouflage. Surfaces with tailored absorption properties for electromagnetic radiation can reduce radar and infrared signatures. Nanostructured material can result in stronger light armour, but it is unclear whether it could offer improvements over heavy armour. Nanofibre-based garments can provide better protection against projectiles.
- *Soldier-worn systems* could sense the state of health of the wearer and react by releasing drugs or, using smart materials, by compressing wounds. Energy for communication could be generated by normal body movements.
- Employing advances in materials and explosives, conventional *guns* could shoot to larger ranges at reduced mass. With NT-based guidance systems, targeting accuracy could increase markedly. The same holds for *missiles*. With respect to penetrating projectiles, it is unclear whether NT-designed materials and structures will transcend the properties of tungsten or (depleted) uranium. Whether NT-based armour will prevail over NT penetrators or vice versa is an open question.
- With NT, the size of *autonomous mini- and microrobots* could decrease, principally down to far below 0.1mm. These could move in all media: on the ground, in water and in air, using propulsion principles known from larger technical systems (wheel, track, propeller, wing, jet, rotor) or biomimetic ones (using legs, wriggling like a snake, hopping, using flapping wings, flagella, etc.). Mini-/microrobots could be designed for a wide variety of purposes – such as reconnaissance, communication,

[15] A sensor usually converts some property of the surroundings – such as temperature, patterns of light, magnetic field strength – into an electric voltage and then processes or transmits this information.

target designation for larger weapons, actuation on a small scale – or as weapons. Speed and range would be limited, but mobility could be aided – for example, by wind – or they could be transported first by grenades, missiles, etc. Capabilities for sensing, communication and actuation would decrease with shrinking size. Such limitations, however, could be compensated for by close range or mass use. One possible scenario would involve entering into a target object or subject and approaching a central node; there the robot could eavesdrop, manipulate or destroy. Another possibility would be acting in high numbers, choking air intakes, blocking windows, putting abrasives into mechanics, etc. Biological–technical hybrids, such as insects or small mammals controlled by nerve/brain electrodes, could fulfil similar purposes. Thus, they should be classed with mini-/microrobots.

- For *systems implanted into the human body*, NT would provide improved possibilities over microsystems technology (MST). One type of application would monitor the medical and stress status of a soldier, releasing therapeutic drugs, hormones, etc., as necessary. Another would have electrodes connected to sensory organs, sensory nerves, motor nerves or muscles – or to the respective brain-cortex areas. This could, for example, be used to decrease the reaction time for pilots. Communicating complex sensory impressions or thoughts, however, requires fundamental progress in brain research and a reduced barrier against human experiments.
- For military uses of outer space, NT (with MST) will provide many possibilities for markedly smaller *satellites*, together with smaller *launch vehicles*. Small satellites could be used in swarms for radar, communication or intelligence. Owing to the large effective antenna size of such a system, the target resolution would be high; however, the total antenna and solar-cell area would determine the strength of received or transmitted signals. Small satellites could damage or destroy other satellites – either by a direct hit with high relative velocity or through manipulations after rendezvous and docking. NT-enabled electromagnetic acceleration could also be used for kinetic-energy space weapons.
- For *nuclear weapons*, no qualitative change is expected. NT will allow smaller guidance or safety/arming/fusing systems. However these would not change basic weapon properties, mainly the requirement for a critical mass of uranium or plutonium for a fission explosion, leading to a total mass of at least 70 kg. An exception might be hypothetical pure-fusion weapons without a fission primary, where the fusion fuel would be ignited at a microspot using MST/NT. The yield could be arbitrarily low, and the size and mass correspondingly small, blurring the distinction with conventional weapons. In one scenario, a minute amount of antimatter would be kept safely in a microtrap until released onto

lithium deuteride (Gsponer & Hurni, 2000: 130–134; Gsponer, 2002). Such possibilities are speculative at present, but should be followed up systematically.

- With respect to *chemical and biological weapons*, on the other hand, NT will provide qualitatively new options. One might be capsules that enclose active agents more safely, releasing them only when required. Together with improvements in genetics, NT may enable chemical/biological weapons (the difference becomes fuzzy here) that selectively react to certain gene patterns or proteins. Such weapons could be targeted at certain ethnic groups or even single individuals, or might act against animal breeds or plant varieties. NT could also be used for easier entry into the body or its cells. Mechanisms could be designed that limit or prevent damage to own forces, such as self-destruction after a defined period of time or reliable inoculation. The outcome of all this would be to make biological warfare much more manageable and effective. On the other hand, NT might permit more sensitive sensors for chemical or biological warfare agents. NT materials with high active surface areas could be used to bind and neutralize agents, or they could be used in protective equipment and for decontamination of affected areas.

Most applications will need 10 or 20 years to mature. Not all need turn out to be feasible, effective, cost-efficient and sufficiently robust to countermeasures. Several will be developed in parallel or chiefly in the civilian realm, in particular where a mass market is foreseen. Here, military uses may be driven by civilian technology. On the other hand, the military will continue to lead in many high-risk areas, sometimes paving the way for later civilian uses.

Because of the wide variety of effects, various combat countermeasures that would make massive use of NT themselves are to be expected, of course at the respective technological level available. For countering NT-based weapons, armed forces could make increasing use of autonomous systems, protect own systems passively (encapsulation, molecular-size sieves) or defend actively (reactive surfaces against adhering objects, 'guard' micro-/nanorobots). The effectiveness of weapons vs. countermeasures is unclear at present. However, there are no indications of defence dominance, so counter-attack and preventive attack will likely play an important role in armed conflict.

Some military uses of NT would not create concern (e.g. soldier health systems); some would be so close to civilian developments that limitation will be excluded (e.g. improved computers); and some could even contribute positively to protection of civilians and disarmament (e.g. sensors for biological agents). However, a number of applications are likely to bring dangers, as will be discussed in the next section.

The special nature of *molecular NT* raises particular concerns. As noted, the feasibility of molecular NT is disputed. Should its development become realistic, possibly in a few decades, self-replicating molecular assemblers would at first produce their like, then potentially larger machinery on many size scales. Finally, at the end of the production process, arbitrary goods could be made (see note 2 above). In such a scenario, fast, indeed exponential, growth in the production of armaments would be made possible, limited only by resources, energy or transport. Thus, by means of molecular NT a state could vastly enlarge its military production within a short time (Gubrud, 1997).

Whereas assemblers could produce weapons and carriers that are similar to traditional guns, tanks or aircraft, the technology would play to its full advantage in the building of new types of systems that make use of properties characteristic of molecular NT, such as smallness, reliance on locally available resources, very high numbers, very high computing power, a wide variety of sensors and actuators, the ability to enter into objects and organisms, self-replication, etc. Explosion, kinetic-energy impact, electrical/chemical/biological interaction, information attack and other methods of causing damage would be used. Because the mobility of very small objects is limited and because important targets will continue to require considerable energy release for destruction, macroscopic carriers and weapons would not vanish. The nature of the mixture of macro-/micro-/nanosystems that would evolve from the complex interaction between measures and countermeasures cannot be assessed at present. Principally, one will have to expect damaging systems on all size scales, from specially designed poison molecules via nano-, micro- and minirobots to large weapon systems. Potential 'molecular hackers' and terrorists would add to the complexity.

## NT and Preventive Arms Control

When new military technologies are seen in the context of an interacting international system and enlightened national interest, they often increase threats and reduce stability. For preventing or at least reducing such risks, limitations can be agreed upon in advance, before new weapons or technology are deployed, acting mainly at the stages of development and/or testing, and sometimes at the research stage. Precedents for preventive arms control – a variant of qualitative arms control – exist explicitly or implicitly (for example, in the – now defunct – Anti-Ballistic Missile Treaty of 1972, the Biological and Chemical Weapons Conventions of 1972 and 1993, respectively, the nuclear testing treaties of 1963 and 1996, and the Protocol on Blinding Laser Weapons of 1995). Ideally, preventive arms control consists of four steps: (1) prospective scientific-technical analysis of the technology in question (properties of weapons, propagation, effect on targets); (2) prospective analysis of military and operational aspects (probable use, targets, unusual employment forms, collateral effects); (3) assessment under the criteria of preventive arms control; and (4) devising possible limits and verification methods that do not impede positive uses and keep costs within reasonable limits. Studies of the various potential military applications of NT have yet to be carried out. However, significant concerns arise when one considers the three areas of preventive arms-control criteria.

### *Dangers to Arms-Control Agreements and the International Law of Warfare*

Existing arms-control agreements, such as the Biological Weapons Convention, might be undermined by new agents based on NT-enabled progress in biotechnology. (On the other hand, strengthening of the Biological and Chemical Weapons Conventions might be possible through new NT-based sensors or materials for neutralization.) Also, limits on conventional forces could be circumvented by new weapons types not covered by treaties or outside treaty definitions – for example, by autonomous microrobots or electromagnetic guns below the 75mm-calibre threshold for tanks under the Treaty on Conventional Armed Forces in Europe.

Moreover, the international law of warfare could be endangered – for example, through the introduction of autonomous fighting systems producing superfluous injury or not reliably recognizing non-combatants or combatants *hors de combat*.

### *Dangers to Stability: Attacker Advantage, Arms Races and Proliferation*

Destabilization of the military situation between potential opponents is probable with the more efficient, distributed data-processing systems as well as omnipresent sensor nets and smaller weapons that NT will make possible. Pressures to act fast will increase with mini-/microrobots; these could be sent into an opponent's territory already before hostilities begin, ready to strike on command, heightening uncertainty and nervousness. Other dangers could ensue from the need to delegate more decisions to autonomous systems because waiting for human pondering could lead to clear disadvantages. Unintended action–reaction cycles might evolve between opponents' systems of warning and attack.

Arms races have to be feared in all areas of military NT use. Even though the USA would probably remain in the lead, several potential opponents could follow up with only years of delay. In anticipation, the USA will work on countermeasures at an early stage. Others might react by increased reliance on asymmetric warfare, including attacks against infrastructure or using weapons of mass destruction.

With respect to horizontal proliferation, transfer of technologies, materials and knowledge is to be expected, as are direct exports of complete NT-based military systems. The problem of proliferation will grow as systems similar to military ones begin to pervade civilian society; examples are microsensors and robots, wearable ultra-small personal computing devices, light vehicles, energy storage, implanted systems, etc. The smaller the system, the more difficult it will be to prevent covert exports.

### *Dangers to Humans, the Environment or Society*

Dangers to humans or the environment could ensue from new NT materials, propellants, etc., as well as from exploration of new damage mechanisms for weapons. However, these effects could largely be contained by civil society regulation, except in cases where military regulation is less strict.

Society could be detrimentally affected in a variety of indirect ways – for example, through diffusion of the technology. One such way might involve state agencies, enterprises, private persons or criminals (singly or organized) eavesdropping through the use of microsensors and robots. Another might involve the use of small autonomous systems for criminal attacks – and in particular terrorism – including attacks on critical infrastructures. A third possibility is implanted systems and other forms of body manipulation for 'improving human performance'. Deciding what kinds of body manipulation should be permitted under which circumstances is a problem of peacetime civilian life, and should be handled by civilian society. However, military R&D and deployment of such systems could establish a *fait accompli* before society is able to carry out a thorough debate on the desirability of particular technological developments.

### *Preventive Arms-Control Criteria and Molecular NT*

In a molecular NT scenario, all of the above problems would exist with much higher urgency (Gubrud, 1997). Military robots with sizes from nanometres to metres would bring threats on an unknown scale.[16] If they could kill, they could constitute new forms of weapons of mass destruction more potent than known biological warfare agents. With non-lethal effects, such as dis-

[16] In principle, replicating nanorobots could also be released unintentionally, in the worst case consuming all organic material, fast converting the biosphere into 'grey goo'. Freitas (2000) has argued that this is fairly improbable. The Foresight Guidelines on Molecular Nanotechnology (Foresight Institute, 2000) contain the principle that artificial replicators must not be capable of replication in a natural, uncontrolled environment, and they discourage evolution within a self-replicating manufacturing system. Keeping such rules is obviously more difficult if unrestricted military R&D tries to find out what is possible.

ruption of personality, mass attacks could lead indirectly to the breakdown of a society and the death of a large portion of its members. Partly as a result of their smallness, but mainly owing to their potential for self-replication and the production of additional weapons on site, nanorobots would create extreme uncertainty. Pre-deployment against an opponent would be easier. The pressure to act fast and to use automated decisionmaking would grow. Unintended action–reaction cycles could work at all levels, from molecules to large-scale decisionmaking. Motives for preventive attacks would exist for both technologically leading and technologically lagging powers. Molecular NT would also create unknown arms-race levels as a result of attempts to maintain or increase a technological advantage, or to catch up. The urgency would be greatly increased if one assumes capabilities for fast-growing autonomous military production. In theory, the very first user could achieve a runaway advantage, with ensuing world dominance. This would create massive pressures to proceed as fast as possible if autonomous production draws close. Horizontal proliferation would be nearly unavoidable with small, self-replicating systems – in principle, a single copy would be sufficient for growth in another country or substate entity. However, reprogramming of targets etc. might be needed for unauthorized copies, and sophisticated security measures would need to be overcome. Molecular NT used for military purposes could also result in increased dangers to humans, the environment and society. Diffusion of systems and technology to criminals and terrorists could hardly be avoided, opening up new options for crime and manipulation. The consequences of accidental releases of nanorobots could be contained if reproduction capabilities were limited and autonomous evolution reliably prevented.

## Conclusions and Recommendations

As discussed above, military NT applications have great potential for dangers and risks, even if molecular NT may remain unrealizable. Thus, there are good reasons to analyse the problems and to think about preventive limits at an early stage. Such studies have yet to be carried out, but already a few considerations suggest themselves.

Because of the fundamental nature of NT, because misuse could occur in both the military and the civilian realms, and because such misuse could come about via military as well as civilian systems, any limits on NT clearly need to encompass both realms simultaneously, even though the rules could differ between both. Thus, national regulations and international controls should be coordinated closely.

Likewise, verification of compliance would be required not only in military institutions, but also in civilian ones. In bio-NT, as well as in the case of specific limits on other micro-/nanosystems, verification would probably have to be at least as intensive as foreseen in the Draft Protocol on Verification negotiated for the Biological Weapons Convention. This protocol – with declarations, laboratory inspections by managed access, etc. – might form a good starting point. It is therefore unfortunate that the USA has stepped out of this important international process. Parallel regulation in the civilian realm could follow the proposal of a bio-security convention (Tucker, 2003). With respect to other new weapons types having macroscopic sizes, access to test ranges together with notifications on military R&D may suffice.

The potential for mistrust is expected to be particularly high in areas where revolutionary changes are foreseen and the speed of those changes can change rapidly. Thus, transparency about national NT initiatives is of immense value and can significantly contribute to building confidence. Formally agreed confidence- and security-building measures about NT R&D might range from information exchanges on projects and budgets to direct cooperation, including exchanges of scientists and engineers. Such informal and formal measures should be striven for on many levels. However, it is doubtful whether they would suffice without legally binding agreement with stringent verification covering military NT R&D.

Many of the military NT applications could arrive 5 to 15 years from now. Some would mostly serve for defensive protection, including protection against terrorist attacks. Others will arrive inevitably because of parallel civilian developments. Seen from today, the most problematic areas in the medium-term future seem to be new chemical/biological weapons, miniature anti-satellite weapons, autonomous fighting vehicles of all sizes, small robots for various purposes and body implants. Consequently, the following general recommendations might be given:[17]

- Existing arms-control/disarmament treaties and humanitarian international law should be upheld, and the Biological Weapons Convention strengthened.
- A comprehensive ban on space weapons should be concluded, possibly with special rules for mini-/microsatellites and carriers.
- Autonomous 'killer robots' should be prohibited.[18]
- For small, mobile artificial systems (including biological–technical hybrid systems), specific restrictions should apply.[19]

[17] In part based on my recommendations for MST (Altmann, 2001), expanding on Altmann & Gubrud (2002).

[18] Uninhabited military vehicles/robots with or without combat function need a differentiated analysis; for first considerations, see Altmann (2003). The least one should demand is no autonomous use of deadly force (keep a person in the loop at all times).

[19] One concept of such restrictions would be a ban below a certain size, for example, 0.2–0.5m, with narrowly circumscribed exceptions for important civilian purposes, as proposed for MST (Altmann, 2001).

- Body implants that are not directly medically motivated, including mobile micro-/nanosystems for movement/operations within the body, should be subject to a renewable moratorium of, say, ten years' duration.

To support efforts in these directions in the short term, the technologically leading nations should exercise unilateral and coordinated restraint with respect to military NT activities, in particular de-emphasizing or avoiding those that could lead to offensive uses. NT R&D should be extensively published, in both the civilian and the military realms. In particular, states that are traditionally less open about their military R&D should increase their transparency to avoid creating unnecessary mistrust. The nanotechnology initiatives of various nations should work together to build confidence and to address concerns such as arms control and safety protocols. The various efforts at international outreach and cooperation carried out by the US NNI are to be commended here (Roco, 2001, 2002b).

Future research should study the foreseeable military applications in depth from the viewpoint of preventive arms control. Verification investigations should focus on the detection of small objects/activities by cooperative technical means deployed on site (an interesting area could be such means that are themselves based on NT).

A specific responsibility of technology assessment, not only in the military realm, is to look scientifically into molecular NT. For responsible decisions, it is indispensable to clarify whether self-replicating nanorobots, universal molecular assemblers, nanorobots that act within the body, etc. can be realized, and, if so, in which time-frame. The widespread impression that these concepts can be safely discarded as pure science fiction is not backed up by serious research, and the proponents' findings have not been decisively refuted. Measures to limit dangers from self-replicating artificial nanosystems would be needed as soon as the feasibility of such systems comes into sight.[20]

As in other technology areas, it is probable that the USA will be without a serious technological challenge from a potential military opponent in military NT R&D. This implies that unilateral restraint by the USA would not lead to threats to the USA from NT in the hands of such opponents for quite some time. Theoretically, this could buy sufficient time to agree internationally on appropriate, reliably verifiable limits. This will require the technology leader to understand that restraint is in its own best interest. Such an understanding is not commonly found with the present US government or military. It could grow, however, when it becomes obvious that, through arms competition and proliferation, technologies and systems developed in the USA at high cost could in the future also be used against the USA, be that

[20] The Guidelines of the Foresight Institute (Foresight Institute, 2000) may serve as a starting point. In particular, their exclusion of agreements on the military sector should be amended.

by terrorists, agents or military opponents,[21] with negative consequences for the USA. Previous examples (the Anti-Ballistic Missile Treaty 1972–2002, the Laser Blinding Weapons Protocol 1995) show that under certain conditions the USA can be receptive to such arguments of enlightened national interest.

In the long run, one cannot dismiss the thought that containing the risks of new and powerful technologies such as genetic engineering, pervasive computer networks, microsystems and nanotechnology may become difficult in a world in which security is built mainly on the threat of military force. Reliably preventing misuse and adequately ensuring compliance may require far-reaching limits, intensive verification and an effective system for criminal prosecution of transgressors, similar to what has been developed and become accepted within civilian society – for example, in the fields of workplace security, the environment, accounting and law enforcement. Long-term security thus calls for strengthening of law and political institutions at the international level, including international criminal law, while reducing the dependence on national armed forces.

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[21] There should be little doubt that technologically capable countries such as China or Russia that (have to) see themselves as potential opponents of the USA would be able to follow, though with some years' delay and qualitative disadvantage. Nevertheless, with the potential for asymmetric action and exploitation of vulnerabilities, very disturbing threats to the USA would likely ensue.

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