Anticipating Military Nanotechnology

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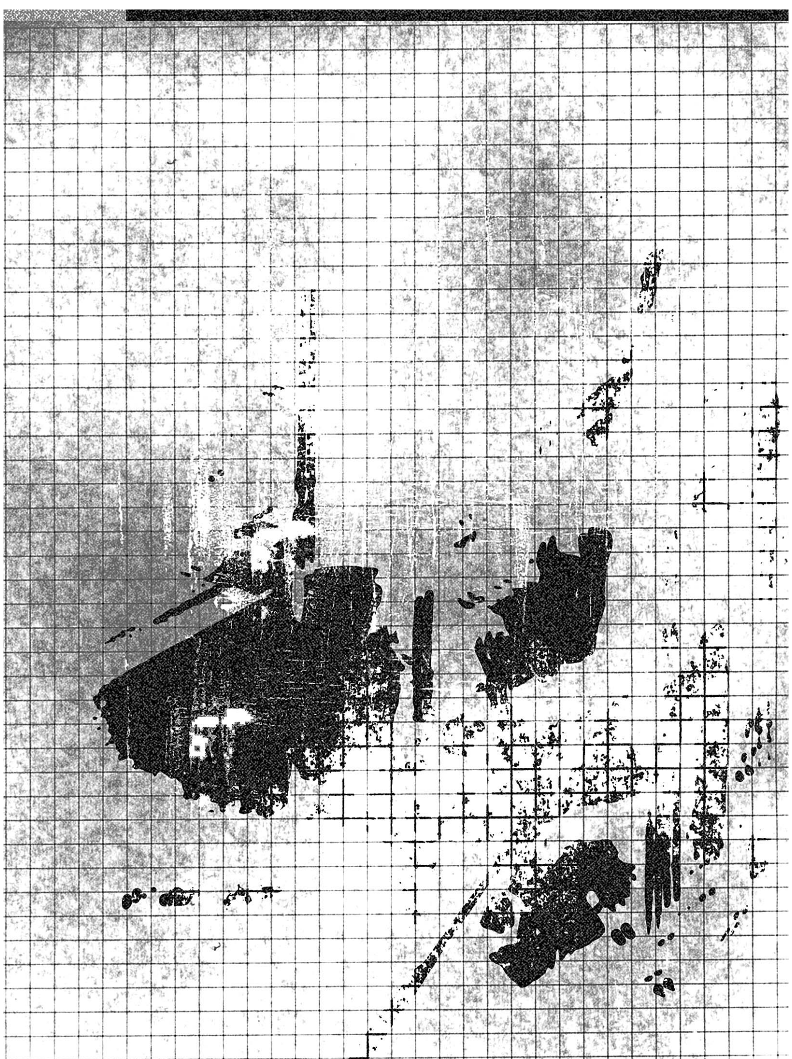

Is the Kevlar helmeted, body armored, night-visioned soldier of today merely a preview of the nanotechnology-outfitted soldier of tomorrow? According to some military visionaries, warriors will wield rifles that fire small self-guided missiles, dispatch flying mini-robots and microsensor nets as scouts and sentries, and carry devices that can gather water in any environment. They will be networked to tactical command through helmets that provide an "augmented reality" overlaid with information and instructions. They will jump six-meter walls assisted by active uniforms that also stop bullets, bind wounds, regulate body temperature, and monitor vital signs. Implanted with biocontrols, they will be ready for up to a week's continuous alertness without suffering effects of sleep deprivation.

Seldom mentioned is what happens when the high-tech soldier encounters a low-tech grenade. Even nanotechnology (NT) provides no immunity to conventional explosive devices, heavy-caliber ballistics, chemical and biological agents that manage to penetrate the layers of protection, or nuclear weapons.

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Likewise missing from most scenarios are the high-speed, high-stealth, high-impact NT-based weapons that may be deployed against the nano-soldier. Will one side hold a monopoly on this technology, facing only hopelessly under-equipped guerrillas or the creaky military machines of backward dictatorships? Or will nanotechnology fuel a new arms race and global confrontation?

Nanowar hype has begun to go global. Shimon Peres, former Prime Minister of Israel opened a Dutch-Israeli NT conference on 15 April 2004, saying:

> A nano-uniform for American soldiers will be lighter than cotton, but protect them against bullets and gas, regulate their body temperature, and enhance their strength. They can easily lift 120 kg with one hand. This new uniform will be available in three years [1].[1]

At a celebration of the Weapons and Electronic Systems Engineering Establishment (WESEE) of the Indian Navy on July 1, 2004, new Indian President A.P.J.Abdul Kalam asked the country's scientists to make a breakthrough. He asserted that nanotechnology would lead to faster and ultra-miniaturized computers and would influence the strategic sectors with rolling out of nano-satellites, stealth structures and nano-vehicles, and even smart clothes and shoes. Kalam said after their success in software, India should keep abreast of this amazing technology. He said carbon nanotubes and its composites would give rise to super-strong, smart, and intelligent structures in the field of material science and this in turn could lead to production of nano-robots with new types of explosives and sensors for air, land, and space systems.

"This would revolutionize the total concept of future warfare," he said [3].

The global security system remains unsettled, threatened by unilateralism, nationalism, and rearmament. Costly arms buildups continue against the backdrop of nuclear dangers, and rapid evolution of technology propels continuous modernization, even where the threat of war is thought to be remote. Given that nanotechnology is being developed simultaneously in many nations, unless military applications are limited by conscious political action *before* they become available, military forces may end up confronting each other with NT-based weapons. They may find themselves confronting criminals, terrorists and rogue states armed with such weapons, as well; other than weapons of mass destruction and some major weapons systems, products of the global arms industry are freely available on the world market, traded at arms fairs and mercenary supply houses.

Nanotechnology and related technology trends, such as robotics and the "convergence" of NT with biotechnology, information technology, and cognitive science (NBIC) [4], [5], are disruptive and transformative technologies that pose fundamental questions for security in the international system of the 21st century.

However, to date there has been little analysis of these issues within the – still underdeveloped –[6] context of "social and ethical concerns" about nanotechnology [7]. Particularly in the United States, nanotechnology and the NBIC vision have been treated as means to provide an overwhelming technological advantage in "the wars of the future"; little consideration has been given to challenges and opportunities for arms control and cooperative approaches to international security.

We briefly survey military NT efforts in the United States, the nation that is leading where others may follow. Next, we discuss the broad range of potential uses of NT by armed forces, and suggest some of the most pressing problems that could result. Finally, we consider an approach for cooperative regulation [8].

Military R&D of Nanotechnology in the U.S. [9]

The United States accounts for two-thirds of global expenditures for military R&D ($52 billion in 2002, followed by France and the U.K. with a combined $7 billion, then Russia and China, combined about $3 billion)[2] [10]-[13]. Since the Second World War the U.S. has been the first to introduce many new military technologies, so it comes as no surprise that in the U.S. National Nanotechnology Initiative (NNI - the U.S. government funded nanotechnology program that began in 2000), the military takes a considerable share of the funds: between 26 and 32 percent in fiscal years 2000-2004, in 2004 running at $ 222 million [14], [15]. Spending figures for other countries are difficult to obtain, but judging from the U.K. effort in the range of $ 2-3 million per year [16], the U.S. may outspend the rest of the world for military nanotechnology by as much as a factor of ten. This could narrow if more countries follow the U.S. example and make military NT a high priority.

[1]When the authors asked about this astonishing statement at the M.I.T./U.S. Army Institute for Soldier Nanotechnology (ISN), the response was:

> "Our research will contribute to a battle suit of the future that will be much different than what the soldier wears today. The full realization of that vision is probably 15-25 years away. Between now and then, the soldier uniform will gradually become more high tech, as the Army rolls out technology incrementally. As for lifting 120 kg with one hand, I do not know whether that will ever be a reality. We are working on an actuating polymer that may be capable of acting as an artificial exomuscle, but the technology is still in the very early stages. ... The media has sometimes overstated this research by claiming it will lead to boots that will allow a person to jump over a building. We do not expect that to happen. What is more likely is that this research may lead to artificial muscles that could provide autonomous medical care, acting as a tourniquet for a wound, for example" [2].

[2]For Russia, see [11], [12]. The China estimate of $1 billon is from 1994 [13].

Military nanotechnology is still mostly in the research phase. The Defense Advanced Research Projects Agency (DARPA) is funding work at universities, as are the R&D agencies of the various branches of the armed services (which also carry out research in their own laboratories). DARPA programs cover electronics (e.g., sub-50-nm lithography, spintronics, molecular electronics, nano-scale interconnects), materials (such as nanotubes, conducting or electroactive polymers, magnetic memory, functional fibers for textiles), biology (e.g., nanomagnetic particles to analyze and manipulate biomolecules and cells, cantilever-based atomic-resolution imaging of biomolecules, biology-electronics interfaces, nano-biomolecular motors, assembly of bone and skin, and fast-acting biological-warfare sensors) [17]. The Naval Research Laboratory has founded an Institute for Nanoscience [18]. Here and in the traditional divisions, wide-ranging research is being done in the areas of nano-assembly, -optics, -chemistry, -electronics, and -mechanics. The Army Research Laboratory is working on nanotechnology for chemical and biological defense, structural materials, and particulate materials; in nanoenergetic materials, a focus is on insensitive (i.e., safe against unintended ignition) high-energy propellants with improved burning rate and mechanical properties [19]. The Air Force Research Laboratory is active in biology, electronics, materials, and physics; one focus is energetic nanoparticles for explosives and propulsion [19]. The Defense University Research Initiative on NT (DURINT) gives grants for NT equipment as well as research projects, with project titles ranging from quantum computing via nanotubes to nano-energetic systems [20]-[21].

Efforts are also being made to accelerate actual military applications. The Army is funding the Institute for Soldier Nanotechnologies at M.I.T., founded in March 2002, with $50 million over five years; industry is contributing an additional $40 million [22]. Some 150 staff conduct research in seven multidisciplinary teams, including thrusts in protection, performance enhancement, and injury intervention and cure. One guiding vision is a multifunctional dynamic battle suit that protects against projectiles and chemical/biological agents, provides communications, changes color for camouflage, can apply force for lifting loads or compressing wounds, and senses body state. In December 2002, the Center for Nanoscience Innovation for Defense was founded at the University of California, with cooperation from industry and national laboratories [23]. For faster introduction of NT-based near-term improvements, the U.S. Army has founded a Manufacturing, Research, Development, and Education Center for Nanotechnologies at Picatinny Arsenal, NJ, focusing on smart munitions, fuses, and structural and energetic materials [24]. Two of the three national nuclear weapons laboratories funded by the Department of Energy, Sandia and Los Alamos National Laboratories, jointly founded in 2002 the Center for Integrated Nanotechnologies [25]. Much of its research – in areas such as nano-bio-micro interfaces, photonics and electronics – seems to be general. However, work on specific military applications is probably underway at the laboratories, perhaps continuing the Sandia work on safety, arming and fusing devices using microsystems technology. Beyond generic nanoscale research, the Livermore National Laboratory has reported projects on new nanostructured high explosives with tailored composition and energy release [26], [27]. Part of this work is done in the context of the nuclear stockpile stewardship program – with the plausible consequence that success might lead to modifications in the design of some nuclear warheads.

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Potential Military Applications of NT

Nanotechnology will provide armed forces with many opportunities. Applications common to civilian and military sectors include small, very capable computers, communications, sensors, and displays. They would be embedded in uniforms, weapons, and equipment, and linked into pervasive networks on all levels. In logistics, battle management, and strategy planning, new levels of artificial intelligence would be used; DARPA aims at cognitive computing systems that learn and decide autonomously in new situations or allow interactions that are "fundamentally like human-human interactions" [28]. Nanofiber composites would allow stronger, more heat-resistant, but much lighter materials for structures and engines. Vehicles would become lighter, faster, and more agile, while consuming less fuel. Nanostructured membranes for fuel cells and materials for hydrogen storage may make all-electric vehicles a reality. Surface-covering displays may be used for user interface or as variable camouflage.

More specifical military applications include new propellants and explosives of higher energy density, and miniaturized guidance systems for small munitions. Nanostructured material could bring improved penetrators and some strengthening of light armor. Firearms could gain range and accuracy at reduced weight. Small missiles could become practical even against human targets.

Autonomous fighting vehicles and aircraft exploiting advanced and possibly "smart" materials as well as substantial increases in computing power could be built smaller than human-crewed tanks, combat aircraft and helicopters, submarines and boats, although for firepower against heavy targets the need to carry tons of ammunition would limit the size reduction. Vehicles used for surveillance, reconnaissance, and target location could be miniaturized much further.

NT and microsystems technology would permit vehicles and mobile robots of decimeter down to millimeter size, some using biomimetic forms of propulsion. One variant would be to use small animals (rats, insects) controlled by implanted electrodes. Although the munitions payload of small robots would be limited, they could attack at sensitive spots, or act in swarms to achieve a mass effect. Small satellites and launchers may significantly reduce space launch costs; swarms of them could act as large effective radar, communication, or electronic-intelligence antennae. Small satellites could also be effective in attacking larger satellites – by direct hit or by manipulation after docking.

Implants in soldiers' bodies could monitor their health status, and release drugs for therapy – or to influence performance and mood. Identification, communication, or espionage devices could be implanted to keep them hidden. Another type of implant would use electrodes to contact nerves and the brain to reduce the reaction time or to communicate sensory impressions or (simple) information [29].

NT approaches could soon lead to extensions of chemical and biological warfare. Nanoparticles designed to ferry therapeutic drugs across the blood-brain barrier or to concentrate in certain organs could as well deliver harmful substances. A mechanism developed to kill cancer cells after recognition of a mutant gene or protein could be used to target (or spare) a certain group, possibly even a certain individual, on the basis of either genetic factors or some separately administered biochemical marker. Or an agent might be designed to monitor its target's biological status to ensure nonlethal incapacitation. On the defensive side, NT may provide highly sensitive detectors of chemical or biological warfare agents and more effective filters and decontaminants.

DARPA aims at cognitive computing systems that learn and decide autonomously in new situations.

In nuclear weapons, nanostructured conventional high explosive could be used in fission primaries – resulting in lower weight and maybe better compression of fissile-material pits. Safety, fusing, and ignition devices can become smaller. Vastly more capable computers will allow better modeling of weapons physics, including new designs [30]. All this may allow some increase in yield-to-weight ratio, but would not change basic characteristics.

Many of the above concepts may be decades from realization. Practical barriers may limit their utility: micro air vehicles have limited speed, and small systems generally suffer from energy problems. Artificial intelligence and robotics may continue to advance only slowly. Nevertheless, some developments can already be extrapolated, and developments in NT, biotechnology, and information technology will tend to accelerate each other. Because many potential military applications depend on general advance in these technology areas, they would in principle be accessible to all countries with active R&D programs.

Problems from Military NT Applications

Preventive arms control begins with an assessment of the impact of new military technologies on international security, and NT raises flags in several areas (e.g., [31]):[3]

Threats to existing arms control and the law of warfare: New technology can make old treaties seem out of date, and can thereby tempt states to abrogate or disregard them. The Biological Weapons Convention (BWC) could be threatened if new types of agents emerge that are more controllable and more precisely targetable.[4,5] The Treaty on Conventional Forces in Europe might be circumvented by smaller, lighter,

[3]Preventive limitation – prohibiting development, testing and/or deployment – of new weapons types has been part of several arms-control treaties, e.g., the Anti-Ballistic Missile Treaty of 1972 (abrogated by the United States in 2002), the Biological Weapons Convention of 1972, the Chemical Weapons Convention of 1993.

[4]This is particularly problematic since the BWC does not contain a verification scheme; negotiations on adding a Verification Protocol were halted in 2001 when the U.S. announced that it would no longer participate.

[5]Questions could also be raised about the Chemical Weapons Convention, but that well-crafted and well-verified treaty focuses on toxic chemicals and attaches specific, updatable lists of banned chemicals. The greatest impact of NT would be the temptation to use small amounts of toxic chemicals in micro- or nanoweapons.

SECURITY CONSEQUENCES OF ADVANCED NANOTECHNOLOGY

The popular image of nanotechnology has been heavily influenced by visions of what might be possible at an advanced stage of development. Artificial nanosystems may eventually equal or outdo the capabilities of living organisms. Self-replication of microscopic units could enable rapid exponential growth. Advanced NT-based computers could replace human intelligence. Drexler's proposed "molecular manufacturing" would use nanorobotic manipulations, under program control, to flexibly produce a wide range of products with fully integrated nanostructures [34], [35].

The security consequences of such a technology would be profound: Weapons and carriers, with performance characteristics in some respects far beyond what we can achieve today, could be produced autonomously on a vast scale. An early start on exploiting this technology for military purposes could in theory lead to military superiority. This may propel an accelerating arms race and create pressures for preventive attack – by leading as well as lagging military powers, or even between partners. Autonomous weapon systems intermingled in international territory could give rise to extremely fast action-reaction cycles with a high escalation potential. The possibility of covert infiltration of very small, possibly self-replicating robots within enemy territory and systems would create fears of a sudden, stealthy attack. These factors would combine to destabilize traditional deterrence relationships [36].

Advanced NT could bring science fiction to life, creating frightening possibilities for weapons of terror and mass destruction. Reduced costs of nuclear weapons production could stimulate proliferation and expansion of arsenals. Replication and harmful action of bio-nanoweapons might be controlled by specific interaction with cell processes, including recognition of genetic traits. Effects could be engineered for maximum horror: madness, disfigurement, flesh consumed; or passivity might be preferred. If access to the technology is widespread, "molecular hackers" might release actual "viruses," affecting not cyberspace, but the real physical world.

The Foresight Institute has argued against restraint in development of military nanotechnology and explicitly rejects the possibility of negotiated limitation [37]. Instead, Drexler has recommended vigorous efforts to develop defensive "active shields," NT systems designed to recognize malevolent systems and fight them [34]. However, there has been little published work describing such hypothetical defensive systems, nor has any general argument been given that advanced NT should lead to the dominance of defense over offense in weapons and warfare; we think the opposite is more likely [36].

Few scientists think "molecular nanotechnology" is imminent, and some dismiss it altogether. However, there has been too little systematic investigation of the issue to simply ignore the possible dangers. The most important task at present is to get respected scientific bodies to address in a serious way the feasibility of existing proposals and potential time frames for their realization. National and international bodies should then discuss and develop appropriate preventive regulation for any technologies which appear to be both potentially feasible and strongly disruptive.

crewless tanks and combat aircraft that evade the treaty's specific definitions for such weapons.[6] The international law of warfare would be challenged by autonomous combat systems that would be unable to discriminate non-combatants or those disabled or willing to surrender, or that would otherwise cause unnecessary injury. NT applications to nuclear weapons could increase pressures for a resumption of testing.[7]

Destabilization of the military situation between potential opponents: Small, highly accurate and lethal weapons may encourage offensive uses. Deterrence would be weakened if strategic forces could be attacked by non-nuclear means such as stealthy, precision-guided weapons or miniaturized systems covertly infiltrated in advance of an attack. Autonomous systems of confronting powers operating at close mutual range at sea or in space would need to detect and react quickly to any attack, cre-

[6] For example, "Battle tanks are tracked armored fighting vehicles which weigh at least 16.5 metric tons unladen weight and which are armed with a 360-degree traverse gun of at least 75 millimeters calibre."

[7] The U.S. has signed, but not ratified, the Comprehensive Test Ban Treaty of 1996.

WARNING: OBJECT IN MIRROR MAY BE YOURSELF

In the area of new military technology, exaggerated perceptions and worst-case assumptions are common, and can have real consequences.

One U.S. military writer has warned of a Chinese thrust in military nanotechnology [38]:

An article by Major General Sun Bailin of the Academy of Military Science is particularly important because it illustrates how asymmetric attacks on U.S. military forces could be carried out with extremely advanced technology. General Sun points out that U.S. dependence on 'information superhighways' will make it vulnerable to attack by microscale robot 'electrical incapacitation systems' (635).

The targets would be American electrical power systems, civilian aviation systems, transportation networks, seaports and shipping, highways, television broadcast stations, telecommunications systems, computer centers, factories and enterprises, and so forth. Sun also suggests that U.S. military equipment will also be vulnerable to asymmetrical attack by "ant robots".

However, the original article by Sun Bailin [41] excerpted in English in a book edited by the same U.S. author [39], does not mention attacks on the U.S. at all. It turns out to be a report to a Chinese audience about a 1993 study from the U.S. RAND Corporation regarding military applications of micro-electromechanical systems; microscale robots and insect platforms were mentioned primarily as weapons of the U.S. [40].[10]

The present emphasis on military NT in the U.S. and the widely available information about it are bound to have effects on Chinese military planning. Given China's traditional secrecy about military matters, it is plausible that such misrepresentations may in turn increase threat perceptions in the U.S. and reduce motives for restraint and cooperative limitation.

ating potentials for accidental war and uncontrolled escalation. Emerging threats and opportunities may propel qualitative and quantitative *arms races* in all areas of military NT applications, even between non-hostile nations. The dual-use character of technologies for light-weight vehicles, small computers, and implants, will complicate *proliferation* controls. Covert arms exports will be easier with smaller systems.

Dangers to humans and society in peacetime could be posed by new NT-based biological agents, microrobots, and sophisticated weapons in the hands of criminals and terrorists. Very small or even invisible sensors and robots, developed for the military, could be used by state and non-state actors to invade privacy. Implants and other body manipulation might be mandated for wide use by soldiers before society is able to thoroughly weigh benefits, risks, and necessary regulation.[8]

The number and variety of potential problems indicates that instead of stumbling blindly into an era of unlimited military NT exploitation it is worth thinking hard about how to prevent the worst dangers and limit the rest.

Cooperative International Regulation

NT thus poses anew basic questions of how to deal with potential military uses of fundamentally new technologies. NT will pervade industry and society, and the armed forces will not be excluded from making use of highly capable computers, stronger and lighter materials, and the other emerging technical potentials. Some applications – such as highly sensitive detectors for biological agents – might be great assets in helping to verify disarmament agreements and otherwise protect civilian society. Other technical capacities, such as lethal robots or manipulations of the body, will pose critical dangers.

A military-centered perspective may lead to the recommendation that in "deterrence, intelligence gathering, and lethal combat ... it is essential to be technologically as far ahead of potential opponents as possible."[9] A broader approach to national security would try to anticipate the probable reactions of

[8]Note that different countries may show different degrees of restraint with respect to manipulation of soldiers' bodies.

[9]Theme E Summary – National Security, in [4].

[10]Potential enemy and terrorist use against the U.S. was only mentioned in a short paragraph.

potential opponent states: Would they feel threatened? Would they attempt to introduce similar technologies, put more emphasis on weapons of mass destruction, or rely on asymmetric warfare?

We believe that the security of all sides would be served better if the more dangerous applications of NT were reliably and verifiably contained. More than a decade after the end of the Cold War the industrialized and nuclear-weapon states should be able to reach such agreements. It would be tragic if states that are now building partnerships were to find themselves at odds in a dangerous new arms race for failure to consider the implications of new technology.

Most of the specific applications that could be abused – new biological-warfare agents, miniature target-seeking missiles, small robots – would require large R&D programs to bring to fruition. Terrorist groups are unlikely to be able to obtain such systems unless the capable states develop and deploy them on a large scale. Anyone advocating such development and deployment might reasonably be asked to explain why the new weaponry will be less of a threat in terrorist hands than the weapons of recent generations. While there may be compelling reason to develop nano-enabled countermeasures to thwart terrorists' use of existing technologies, going beyond this limited objective via an unrestrained effort to "get it before the bad guys do" risks putting the new technology into the bad guys' hands.

If international limits can be agreed to, including verification and enforcement mechanisms, it is reasonable to expect that they can be implemented. All technological societies already take measures to reduce toxic emissions, improve safety, and otherwise balance costs and benefits; new measures are introduced every year as technology evolves.

While some authors [32] have proposed moratoriums or bans targeted generically on NT, such a blunt approach seeks to arrest progress in chemistry, materials, biotechnology, and electronics. Instead, we recommend detailed consideration of potential dangers or undesirable effects of NT use, with the goal of identifying specific applications or military missions which should be prohibited or restricted, independent of the technology employed. Quantitative parameters of weapons systems, such as the size scale of systems or components, or particular materials used, may in some cases be useful for defining arms control agreements, and in other cases may be irrelevant or unverifiable. The feasibility of achieving agreement to forgo particular applications and to accept the required, possibly very intrusive verification measures, must also be a criterion for evaluating proposed limits.

The security of all sides would be served better if the more dangerous applications of NT were reliably and verifiably contained.

We propose the following guidelines:

- Existing arms control and disarmament treaties and humanitarian international law should be upheld (and updated where needed). In particular the Biological Weapons Convention should be strengthened by a verification protocol.
- All kinds of space weapons should be banned, possibly with special rules for non-weapons use of small satellites and carriers.
- Autonomous 'killer robots' should be prohibited; a human should be the decision maker when a target is to be attacked.
- Small, mobile artificial systems (including biological–technical hybrid systems) should be severely restricted, allowing only exceptional use (such as search of collapsed buildings).
- Body implants that are not directly medically motivated should be subject to a renewable moratorium of ten years' duration.

Banning autonomous killing would not be much of a constraint on present practices, which typically do include a "human in the loop," but such a ban could become extremely important as artificial intelligence is more heavily relied on. Communications difficulties and required reaction speeds would seem to necessitate autonomous decision making for robots to be successful in combat. Do we really want robot wars? It is doubtful whether armed robots should be permitted at all. Currently, their virtues are being extolled for the purposes of remote-controlled assassination and surveillance of combat zones, but the results are questionable.[11]

Following these guidelines, concrete limitations and their associated verification measures will need to be worked out in detail. Small scale does produce distinct verification issues that are also observed in biological and chemical arms control. For system sizes down to about 0.5

[11] In one case, three Afghan peasants were killed because the cameras in the Predator drone were good enough for the remote operator to detect that one of them was tall, but not good enough to determine that he was not Osama bin Laden [33].

m we can to a great extent rely on external observation and on-site inspections of military installations, training grounds, space-launch centers, and other facilities. Limits covering smaller objects may have to include laboratory visits, sample taking, and other more invasive practices similar to those foreseen in the Draft Verification Protocol to the Biological Weapons Convention.

Restrictions on the development of new weapons will be resisted by those who view violence and threats as the foundations of national security, and strong verification measures, including intrusive inspections, will be resisted by both state and private interests. Lest we despair, we should remember that measures adopted to limit nuclear arms during the Cold War were also strongly resisted. Advances in nano-, bio-, and information technology will combine to require increasing levels of regulation and monitoring, within states as well as internationally. Civil society accepts rights of inspection to ensure workplace security, health, and honest accounting, as well as in criminal investigations. The threats posed by powerful new technologies could work as catalysts to strengthen society on the international level, through verifiable arms control, respect for international institutions, international law including criminal law, and supported by lawful security alliances, permitting reliance on national armed forces and preparations for war to be reduced step by step.

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