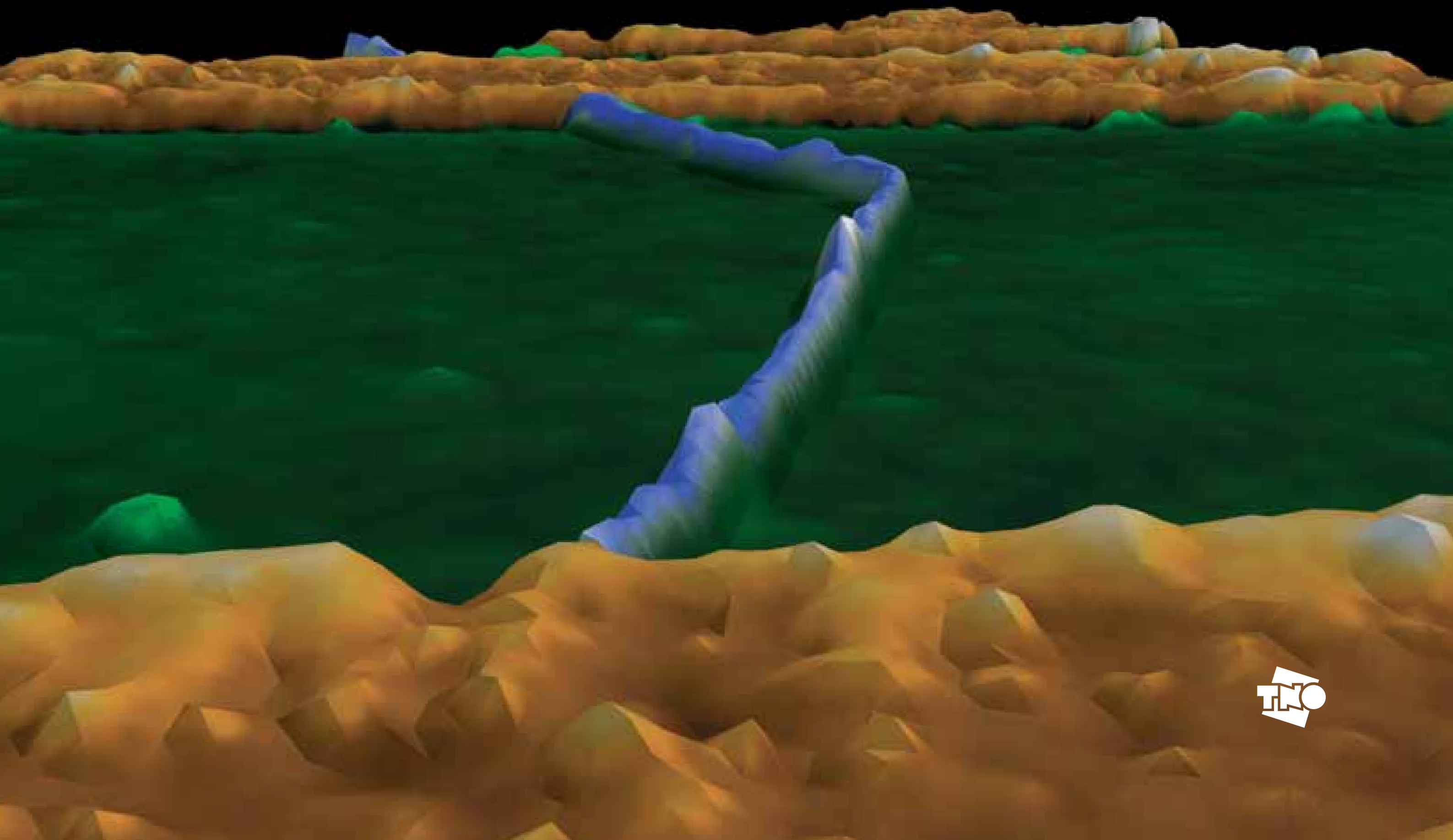
Nanotechnology

innovation opportunities for tomorrow's defence

Frank Simonis & Steven Schilthuizen



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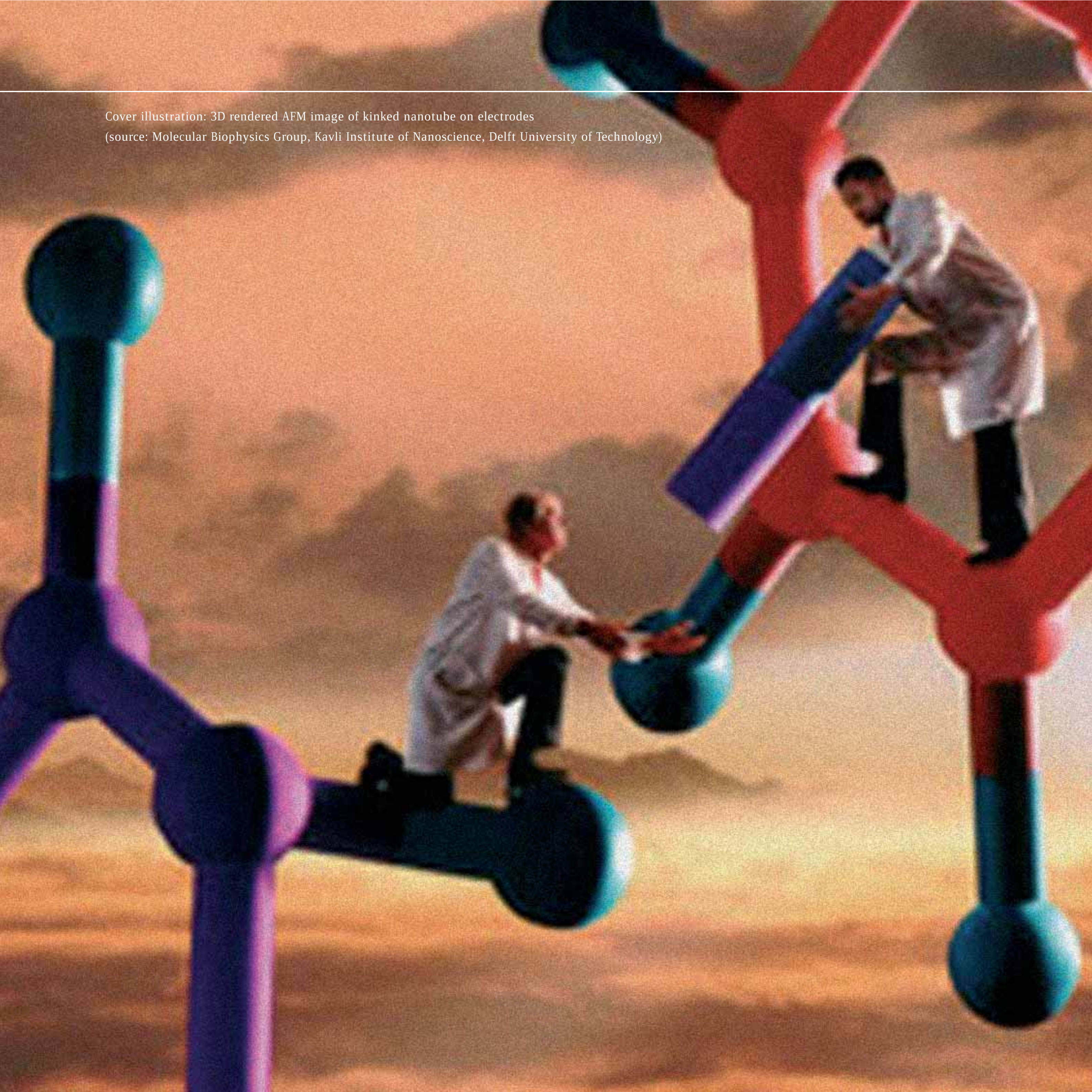


Cover illustration: 3D rendered AFM image of kinked nanotube on electrodes
(source: Molecular Biophysics Group, Kavli Institute of Nanoscience, Delft University of Technology)

Introduction

Hope and hype of nanotechnology

"Nanotechnology is an area which has highly promising prospects for turning fundamental research into successful innovations. Not only to boost the competitiveness of our industry but also to create new products that will make positive changes in the lives of our citizens, be it in medicine, environment, electronics or any other field. Nanosciences and nanotechnologies open up new avenues of research and lead to new, useful, and sometimes unexpected applications. Novel materials and new-engineered surfaces allow making products that perform better. New medical treatments are emerging for fatal diseases, such as brain tumours and Alzheimer's disease. Computers are built with nanoscale components and improving their performance depends upon shrinking these dimensions yet further".

This quote from the EC's "Nanosciences and Nanotechnologies: an action plan for Europe 2005-2009" clearly indicates the hope and hype of nanotechnology, expecting to bring many innovations and new business in many areas. Nanotechnology has the potential to impact upon virtually all technological sectors as an "enabling" or "key" technology including medicine, health, information technology, energy, materials, food, water and the environment, instruments and security. This has lead to a rapid growth of interest and spending in nanotechnology R&D, growing with 40% annually over the last 4 years up to roughly 4000 MEuro in 2004.

(EC: towards a European Strategy for Nanotechnology, 2004)

Impact of nanotechnology on defence

With the highly promising expectations of nanotechnology for new innovative products, materials and power sources it is evident that nanotechnology can bring many innovations into the defence world. In order to assess how these nanotechnology developments can or will impact upon future military operations, the NL Defence R&D Organisation has requested to compile a nanotechnology roadmap for military applications, including:

- survey of current nano- and microsystem technology developments in both the civil and defence markets.
- clarification of the impact on future military operations and organisation, 10-15 years from now.
- guidance on how to translate and adapt such nano- and microsystem technologies into a military context
- a proposal for a Dutch nanotechnology program, taking into account current developments worldwide

How to read this book

This nanotechnology booklet covers the first part of this roadmap study. It provides an overview of current developments, expectations for time-to-market and several future concepts for military applications. The structure is as follows:

- introductory: generic introduction, what is, why and where is nanotechnology in development (1-3)
- technology radar: nanotechnology expectations impacting on future defence platforms, what and when (4-6)
- future concepts: outlook on possible future defence platforms and product concepts, enabled by nanotechnology (7-8)
- strategy: civil versus defence driven developments, opportunities and next steps (9-10)

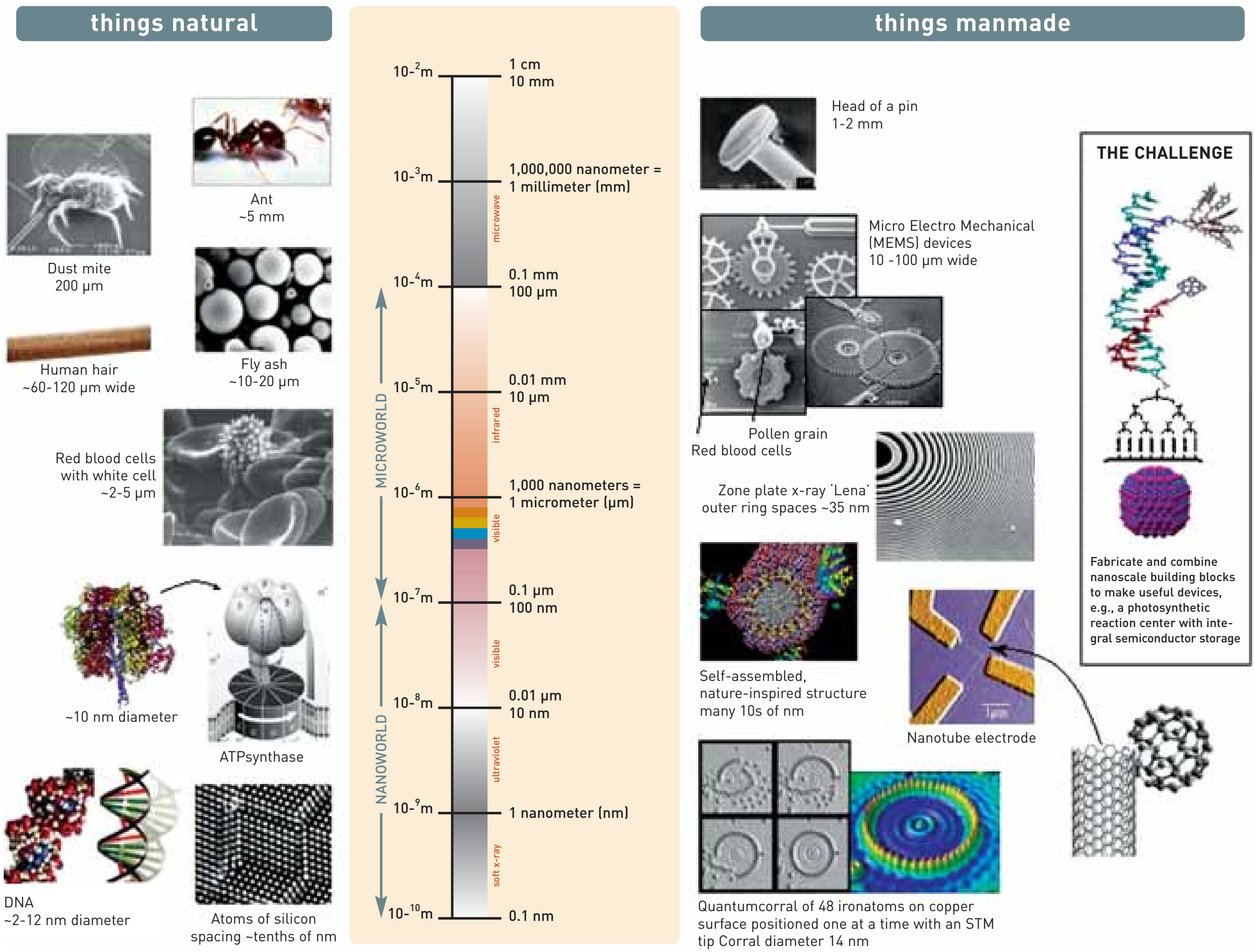
Executives can skim through chapters 4, 7 and 8 that provide technical background details.

We hope this book will serve as a basis for further discussion and decision making on the direction of future nanotechnology developments.

March 2006, TNO Science & Industry
Steven Schilthuizen / Frank Simonis

Contents

The scale of things – nanometers and more



Technology at 10^{-9}m scale

Nanotechnology is the understanding and control of matter at dimensions of roughly 1-100 nm, where unique phenomena enable novel applications. A nanometer is 10^{-9} of a meter; a sheet of paper is about 100,000 nm thick. Encompassing nanoscale science, engineering and technology, nanotechnology involves imaging, measuring, modelling, and manipulating matter at this length scale.

At this level, the physical, chemical and biological properties of materials differ in fundamental and valuable ways from both the properties of individual atoms and molecules or bulk matter. Nanotechnology R&D is directed toward understanding and creating improved materials, devices and systems that exploit these new properties.

(source National Nanotechnology Initiative – Strategic Plan 2004).

The unique properties of nanotechnology originate from:

- small dimensions, enabling high speed and high functional density (nanoelectronics, lab-on-chip), small and lightweight devices and sensors (smart dust), high sensitivity (sensors, nanowires) and special surface effects (such as lotus effect)
- very large surface area, providing reinforcement and catalytic effects
- quantum effects, such as highly efficient optical fluorescent quantum dots
- new molecular structures, with new material properties: high strength nanotubes, nanofibers and nanocomposites

Top-down

Nanostructures can be made by two complementary approaches. With top-down technology nanostructures and devices are made through scaling and miniaturization. It requires precision engineering down to the nano-scale, usually by lithographic patterning, embossing or imprint techniques with subsequent etching and coating steps.

Examples are:

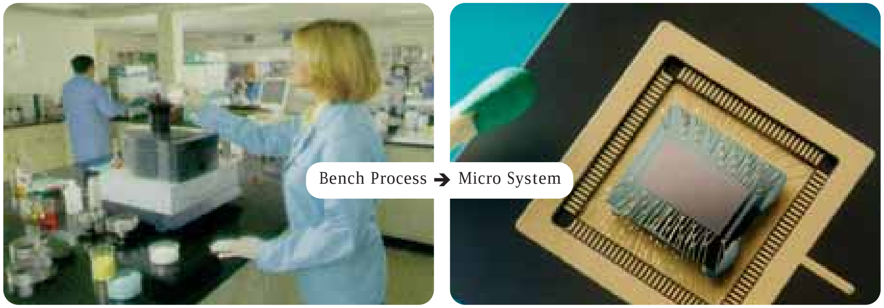
- micro- and nanoelectronics
- MEMS, micro electro mechanical systems
- nanostructures such as lotus coatings, catalytic surfaces and membranes
- nanostructured coatings in displays, solar cells, flat batteries
- nanofibers by electrospinning
- nanoclay platelets and tubes by exfoliation

Bottom-up

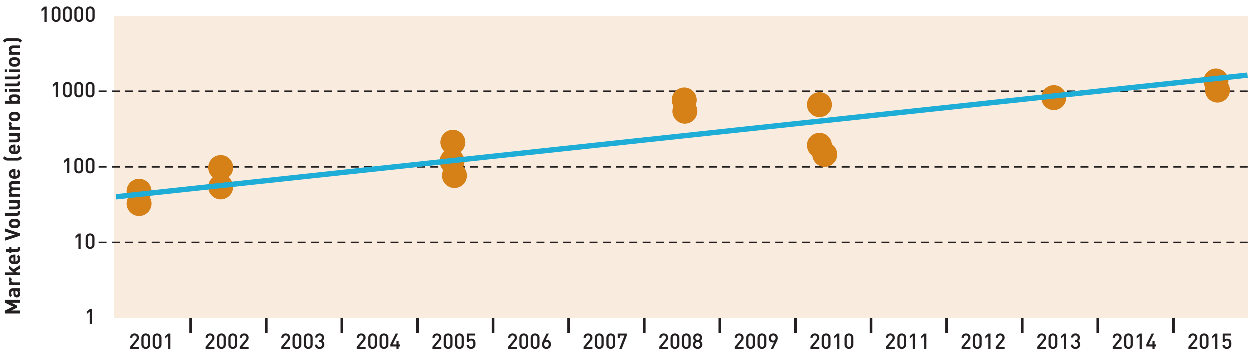
The other complementary route is bottom-up, constructing nanostructures through atom-by-atom or molecule-by-molecule engineering. It usually requires wet-chemical or vapor-phase processing routes such as atomic layer deposition. In some cases atomic or molecular manipulation is applied via optical, electrical or mechanical nanoprobes.

Typical examples are:

- carbon nanotubes by gas phase deposition
- nanowires made from metal, metaloxide, ceramic or even polymer type by gas phase deposition
- quantum dots
- self assembling, molecular and biostructures
- nanomedicine



Exponential market growth for nanotech products



Miniaturisation down to micro & nano level not only leads to smaller products suited for mass production and lower costs, it also enables completely new functionalities that cannot be obtained at the macro level. The new functionalities are gained by physical and chemical effects of the small dimensions, the ability to produce new atomic structures, handling of very small volumes and ratio effects on the natural environment.

Small dimensions: mm > µm > nm

Going to small dimensions offers a large number of advantages for electronic and sensor devices:

- high functional density: nanoelectronics, high density memory
- function integration possible: sensing, dsp, radio, memory and power can be integrated
- efficient and fast electronic, optical, thermal and material transport
- enabling mass production, featuring low costs
- lightweight
- portable, anywhere, everywhere
- disposable

From the material point of view, small dimensions give new opportunities such as:

- control at the nanoscale enables perfect, defect free structures, featuring exceptional properties for strength, conductivity etc.
- nanostructures and particles create a very large surface area, featuring unique surface activity for sensing, catalysis, absorption etc.
- completely new particles, unknown in nature, can be produced with new properties, such as carbon nanotubes
- at the nanoscale, quantum effects can be used e.g. to obtain new optical effects

Small volume: µL > nL > pL

A small volume is especially advantageous for fluidic devices such as measurement devices and chemical processors because of:

- fast response
- high throughput
- multi parallel analysis, matrix array
- single cell/molecule detection
- less chemical waste

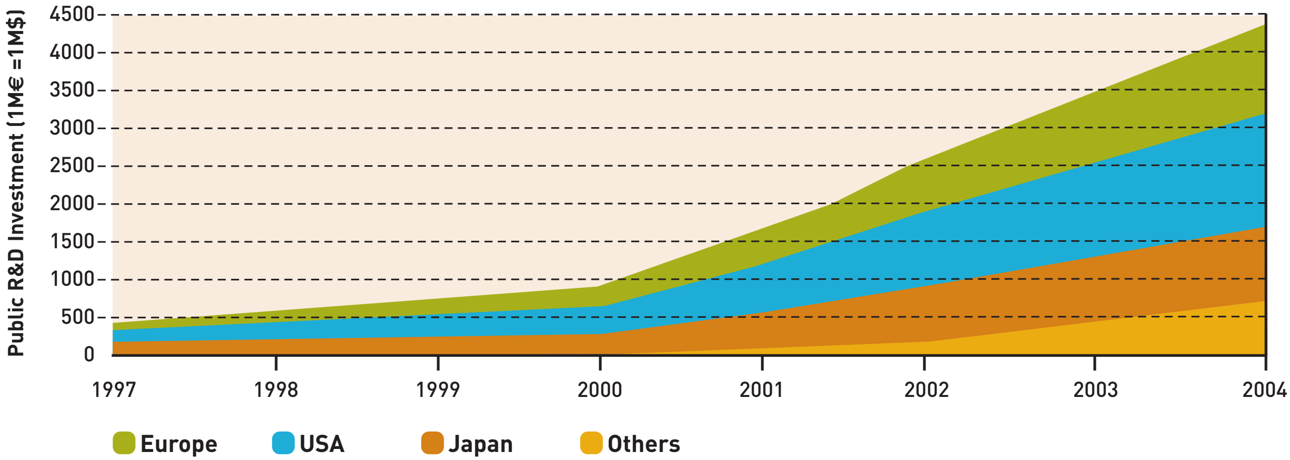
High sensor-sample ratio

Scaling sensor devices down to the nano level brings the sensing element in the same dimensional range as the elements to be detected. This results in:

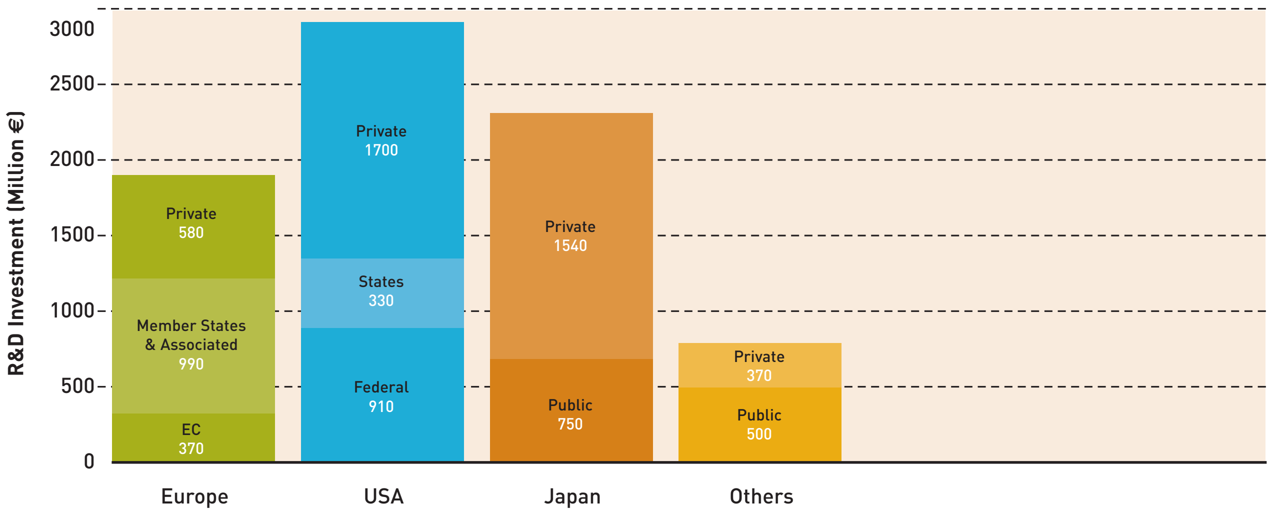
- high sensitivity
- high signal to noise ratios

Evolution of worldwide public expenditure

(1€=1$ to avoid distortions due to exchange rate variations)



Worldwide public and private RD expenditures in 2004



The worldwide run on nanotechnology

Nanotechnology is recognized as a very strong innovation driver and is therefore seen as a strategic technology for the world's future economy. This perception is globally present and many countries invest heavily in nanotechnology through national or transnational nanotechnology programs with high expectations.

Market for nanotech products will grow exponentially

Analysts estimate that the market for products based on nanotechnology could rise to several hundreds of billions by 2010 and exceed one trillion after. Nanotechnology is expected to impact upon virtually all technological sectors as an "enabling" or "key" technology, especially upon:

- medicine and health
- information technology
- energy production and storage
- transportation, vehicles and infrastructure
- materials science
- food, water and the environment
- instruments
- security

Next to the ongoing progress in nanoelectronics, expectations are especially high for:

- nano-bio applications
- nano based sensors
- and nanomaterials in the longer term (10 years)

Public investments show 40% growth annually

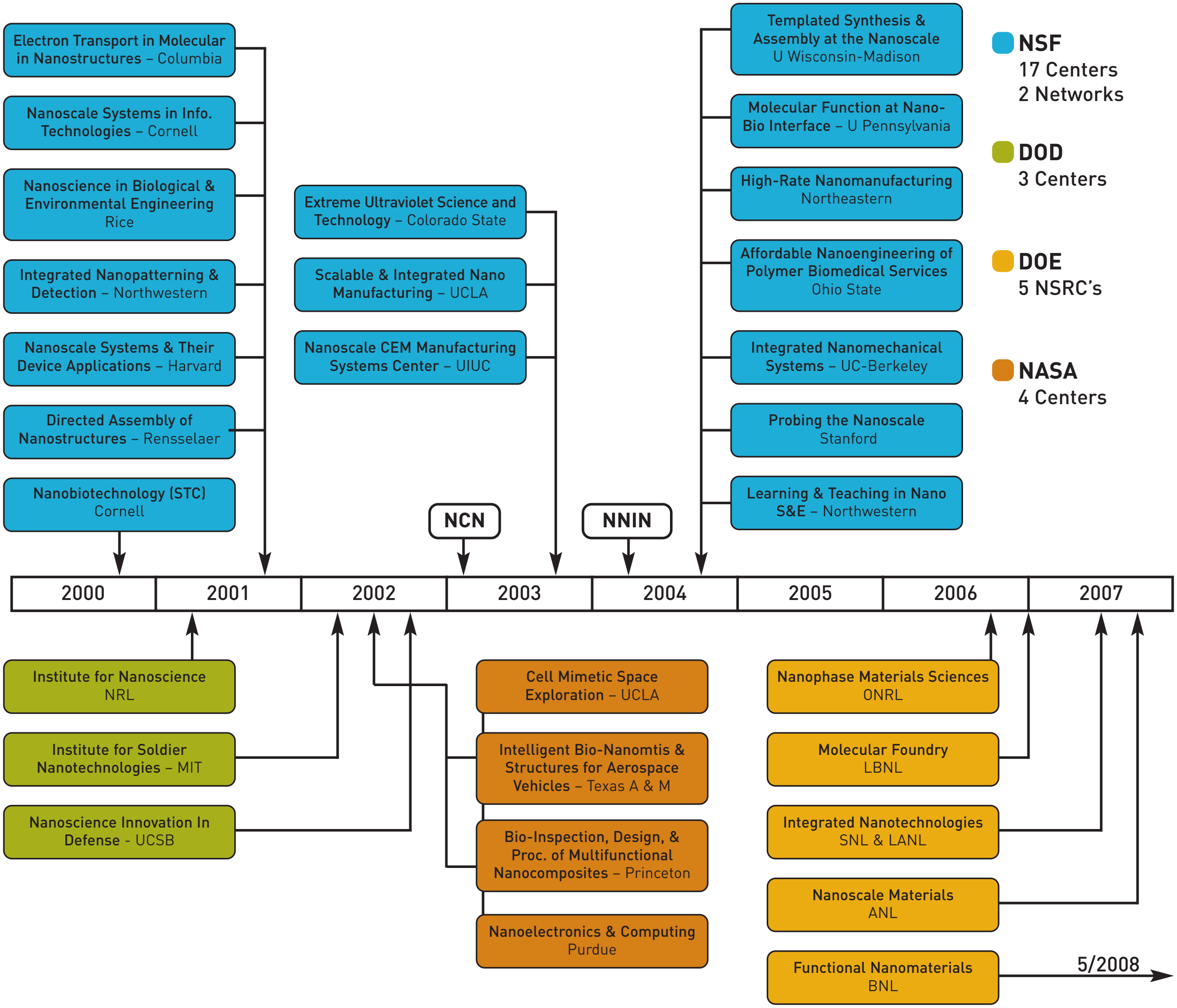
Global public investments in R&D have grown by 40% over the last years and have reached a level of 4500 MEuro in 2004. Top 6 investors (in 2003) with indication of their focus areas, are:

- Europe: nanoelectronics, medicine, materials ~ 1250 MEuro
- USA: all aspects of nanotechnology ~ 1200 MEuro
- Japan: nanoelectronics, nanomaterials, nanotubes ~ 750 MEuro
- S-Korea: high density memory, displays ~ 250 MEuro
- China: mass production nanomaterials ~ 400 MEuro
- Taiwan: display, optoelectronics ~ 150 MEuro
- others: various ~ 150 MEuro

R&D investments doubled by private

The worldwide private expanditures are at the same level as the public investments now. Leaders in the field are the USA and Japan (with 1700 and 1540 MEuro in 2004) followed by Europe and China (580 and 370 MEuro private).

NNI Centers and User Facilities



Source: NNI Strategic plan 2004, Committee on Technology National Science, and Technology Council, dec 2004.

A major step was taken in the year 2000 when the National Nanotechnology Initiative (NNI) was launched. The NNI is a large nationally integrated nanotechnology program that is jointly driven by NSF, DOD, DOE, HHS, DOC and NASA. Since then, 24 nanotech research centers have been formed by NSF, DOD and NASA. The total workforce in these government funded nanotechnology centers now exceeds 6300. Five more research centers are anticipated by the DOE in the next few years. In 2005 the federal NNI funding has reached an annual level of 1000 M$, with additionally 400 M$ estimated funding from the individual states.

Technology

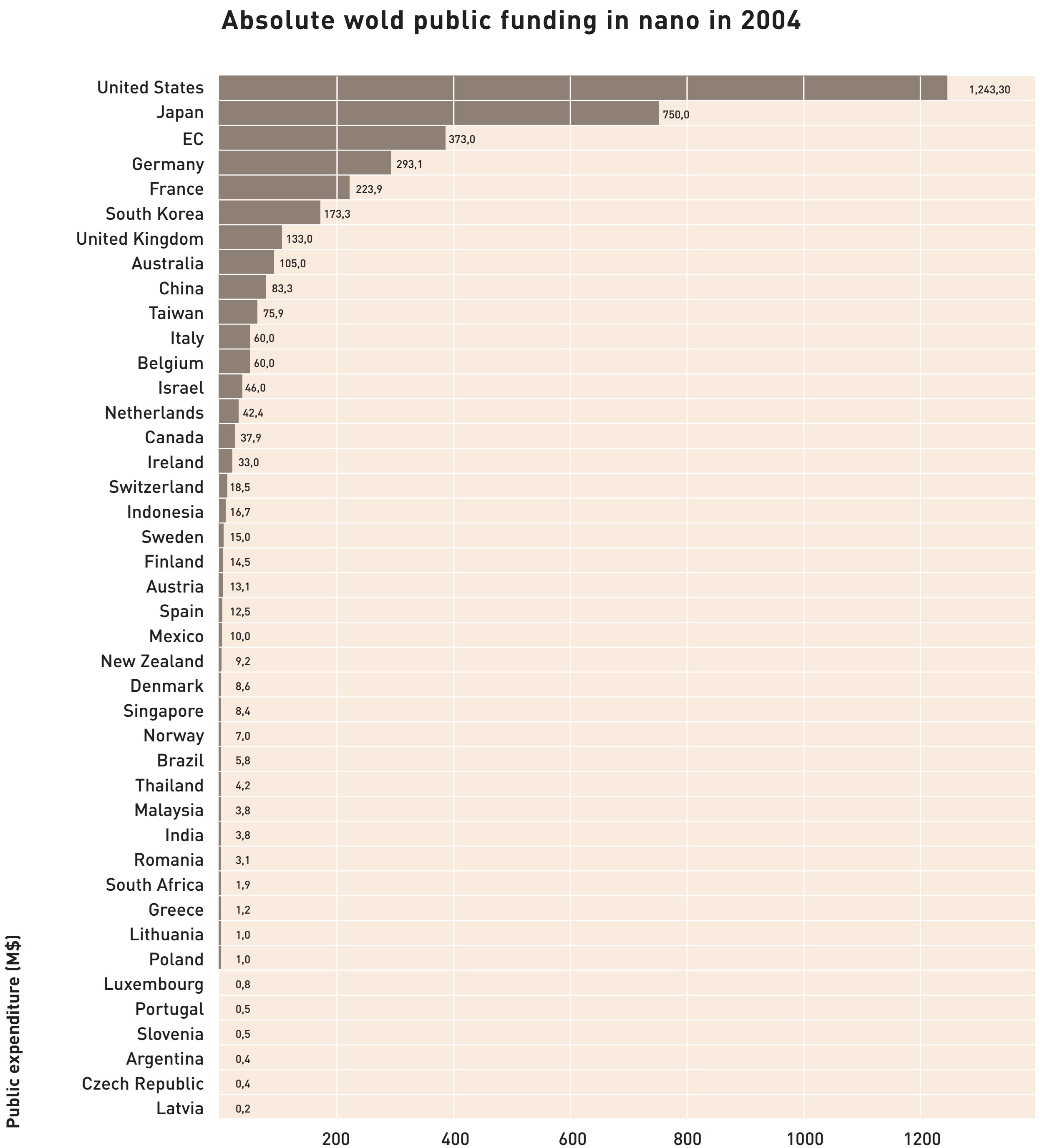
The NNI program covers about all aspects of nanotechnology, spread over seven so-called program component areas (PCA's):

- fundamental nanoscale phenomena and processes
- nanomaterials
- nanoscale devices and systems
- instrumentation research, metrology and standards for nanotechnology
- nanomanufacturing
- major research facilities and instrumentation acquisition
- societal dimensions and nanotech risks

Impact on economy and security

Nanotechnology is seen as a technology of national importance to the economy and security of the US, with a similar impact as semicon in the past. There is a strong belief that nanotechnology will bring many innovations to industry in many sectors and will create strong economic power. The impact is expected to be broad over many sectors:

- aerospace: high strength, low weight, multifunctional materials; small and compact planes; fully automated, self-guided, unmanned air vehicles for reconnaissance and surveillance
- agriculture and food: secure production, processing and shipment; improved agricultural efficiency; reduced waste and waste conversion into valuable products
- national defence and Homeland security: high speed and high capacity systems for command, control, communication, surveillance; automation and robotics for minimizing exposure warfighters, first responders; superior platforms and weapons
- energy: high performance batteries, fuel cells, solar cells, thermoelectric converters; catalysts for efficient conversion
- environmental improvement: improved monitoring; reduced pollution by new “green” technologies; remediation and removal of contaminants
- information technologies: improved computer speed; further scaling of nanoelectronics; reduced power consumption; expansion mass storage; flexible, flat displays; molecular electronics
- medicine and health: novel sensor arrays for rapid diagnostics; composite structures for tissue replacement; targeted, highly effective medicine
- transportation and civil infrastructure: new material composite structure; efficient vehicles; improved safety



Absolute wold public funding in nano in 2004
United States
1,243,30
Japan
750,0
EC
373,0
Germany
293,1
France
223,9
South Korea
173,3
United Kingdom
133,0
Australia
105,0
China
83,3
Taiwan
75,9
Italy
60,0
Belgium
60,0
Israel
46,0
Netherlands
42,4
Canada
37,9
Ireland
33,0
Switzerland
18,5
Indonesia
16,7
Sweden
15,0
Finland
14,5
Austria
13,1
Spain
12,5
Mexico
10,0
New Zealand
9,2
Denmark
8,6
Singapore
8,4
Norway
7,0
Brazil
5,8
Thailand
4,2
Malaysia
3,8
India
3,8
Romania
3,1
South Africa
1,9
Greece
1,2
Lithuania
1,0
Poland
1,0
Luxembourg
0,8
Portugal
0,5
Slovenia
0,5
Argentina
0,4
Czech Republic
0,4
Latvia
0,2
200
400
600
800
1000
1200
Public expenditure (M$)

Japan: 750 MEuro/yr in 2004

In 2004, the budget for the R&D programme for nanotechnology and materials stood at 750 MEuro, but nanotechnology-related themes are also present in life science, environment and information society programmes. This brings the total budget earmarked for the sector in 2004 to nearly 1500 MEuro, with an increase of approximately 20% in 2004. The Japanese private sector is also very much present with 1500 MEuro, represented by two major trading houses, Mitsui & Co and the Mitsubishi Corporation. Most of the major Japanese companies, such as NEC, Hitachi, Fujitsu, NTT, Toshiba, Sony, Sumitomo Electric, Fuji Xerox, etc. have invested heavily in nanotechnology. Priority areas are:

- IT/nanoelectronics
- instrumentation
- nanomaterials, especially carbon nanotube technologies (invented by Sumio Iijima, Japan)
- bio-nanotechnology

China: 85 MEuro/yr in 2004

Under its current five-year plan for 2001 to 2005, China has set aside a budget of approximately USD 300 million for nanotechnology. In 2002, the Chinese Academy of Sciences (CAS) founded Casnec (the CAS Nanotechnology Engineering Center), with an overall budget of USD 6 million, as a platform to accelerate the commercialization of nanoscience and nanotechnology. For 2003 and 2004, the Hong Kong University of Science and Technology and the Hong Kong Polytechnic University have granted their own nanotech centers nearly USD 9 million. An important focus area is:

- mass production of nanomaterials and nanostructures

S-Korea: 175 MEuro/yr in 2004

In 2001 a 10-year nanotechnology program has started.
A Korean advanced nanofabrication center has been created as well as two nanotechnology integrated centers.
Focus areas are:

- nanomaterials and structures, especially carbon nanotube applications (electronics, flat panel displays)
- nanoelectronics and memory
- NEMS devices

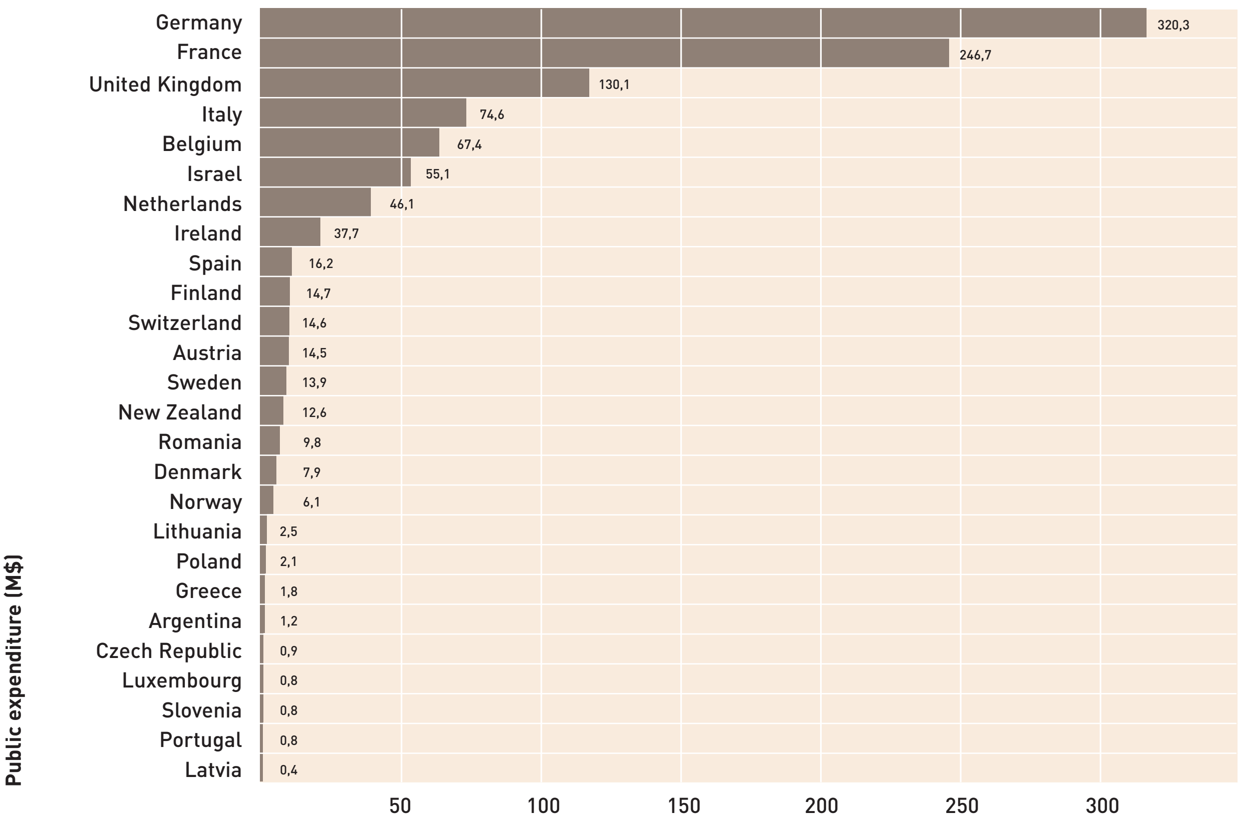
Taiwan: 75 MEuro/yr in 2004

There are two centers for nanotechnology in Taiwan: ITRI for development, transfer and industrialization of nanotechnology and Academia Sinica for the academic/fundamental research. Priority areas are:

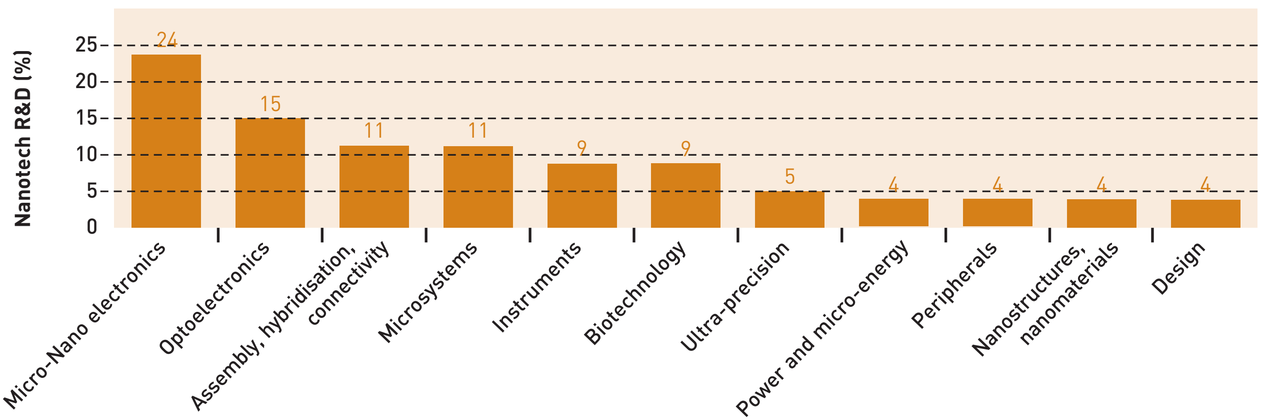
- nanomaterials
- optoelectronics, nonvolatile memory

EU absolute public expenditure in 2004

(PPP corrected and including Countries associated to the EU Framework Programme)



Nanotech R&D in France



Most of the European countries have national nanotechnology programs. In 2004 the individual states invested in total 990 MEuro. In addition to that, the EC spent an additional 375 MEuro on nanotechnology via the 6th framework program. The total investment in nanotechnology is thus equal to or slightly higher than in the US. In contrast to the US, the coordination seems less effective, with quite some overlapping activities among the individual countries. Also the private expenditures lack behind.

In 2005 the EC published a new action plan: “Nanoscience and nanotechnologies: an action plan for Europe 2005-2009”. This plan highlights the following nanotechnology areas:

- nanoelectronics, including nanomanufacturing and nano-instrumentation
- nanobiotechnology and nanomedicine, including diagnostics, targeted drug delivery and regenerative medicine
- nanomaterials, nanoparticle technology
- health and environmental risks of nanotechnology

Germany: 320 MEuro/yr on nano in 2004

Nanotechnology in Germany is focused on nanoelectronics (46 MEuro/yr), nanomaterials (38), nano-optics (26), micro-systems (10), ICT (3), nanobio (3) and manufacturing (2). Nine nanotechnology competence centers have been founded: Nanomaterials (Karlsruhe), Ultraprecision surface engineering (Braunschweig) and nano coatings (Dresden), Nanooptics (Berlin), Nanobiotechnology (Munchen and Kaiserslautern), Nanochemistry (Saarbrucken), Hanse Nanotec (Hamburg); CeNtech (Munster)

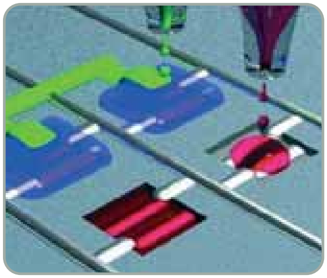
UK: 130 MEuro/yr on nano in 2004

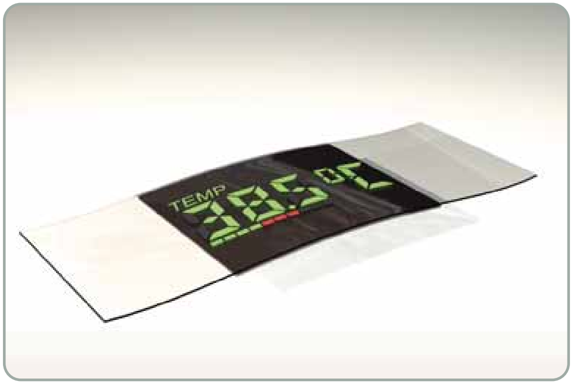
After the National Initiative on Nanotechnology (NION) and LINK nanotechnology program (LNP), both ended in 2002, the UK launched in 2003 the Micro and Nanotechnology Initiative (MNT) to create a network of micro and nanotechnology facilities. At present the UK has 1500 nanotechnology workers. Well recognized nanotechnology centers are at the universities of Oxford, Cambridge, Newcastle, Durham and Glasgow. A special nanomaterials production facility is present at Farnborough, run by Qinetiq. Inex, innovation in nanotechnology exploitation, offers a one-stop-shop facility for micro- and nanosystems including production facilities.

France: 250 MEuro/yr on nano in 2004

The French research structure for nanotechnology is based around a group of five centers of excellence. This network covers the facilities at CEA-LETI in Grenoble (centered on Minatec, which brings together the CEA, the CNRS, the Institut National Polytechnique and the Université Joseph Fourier); the Laboratoire d'Analyses et d'Architectures des Systemes (LAAS) in Toulouse; the Laboratoire de Photonique et de Nanostructures (LPN) in Marcoussis; the Institut d'Electronique Fondamentale in Orsay (IEF) (centered on Minerve) and the Institut d'Electronique, de Microelectronique et de Nanotechnologies (IEMN) in Lille. Priorities are:

- micro & nanoelectronics
- opto-electronics
- microsystems and assembly
- biotechnology and instrumentation





nano ned

MicroNed

Nanotechnology is considered crucial for the high tech industry in the Netherlands, not only for the multinationals such as Philips, ASML, ASMI, DSM, AKZO-Nobel but also for a large number of small and medium sized companies. Three programs are now ongoing.

NanoNed

NanoNed, is an initiative of eight knowledge institutes and Philips. It clusters the nanotechnology and enabling technology strengths of the Dutch industrial and scientific infrastructure. The total budget for this NanoNed program amounts to 235 MEuro (4 years). The program has so called flagship projects on:

- advanced nanoprobing, nano-instrumentation
- chemistry and physics of individual molecules
- bionanosystems
- bottom-up nanoelectronics, nanoelectronic materials
- nanofabrication, nanofluidics
- nanophotonics, nanospintronics

An important part of NanoNed is expansion of the nanotechnology infrastructure called Nanolab in three centers:

- nanolab Grongingen (MSCplus/BioMaDe)
- nanolab Twente (MESA+)
- nanolab Delft (TNO and Kavli – mb/tudelft)

MicroNed

The MicroNed program integrates Netherlands R&D on microsystems. The budget amounts to 54 MEuro (4 years). It has the following clusters:

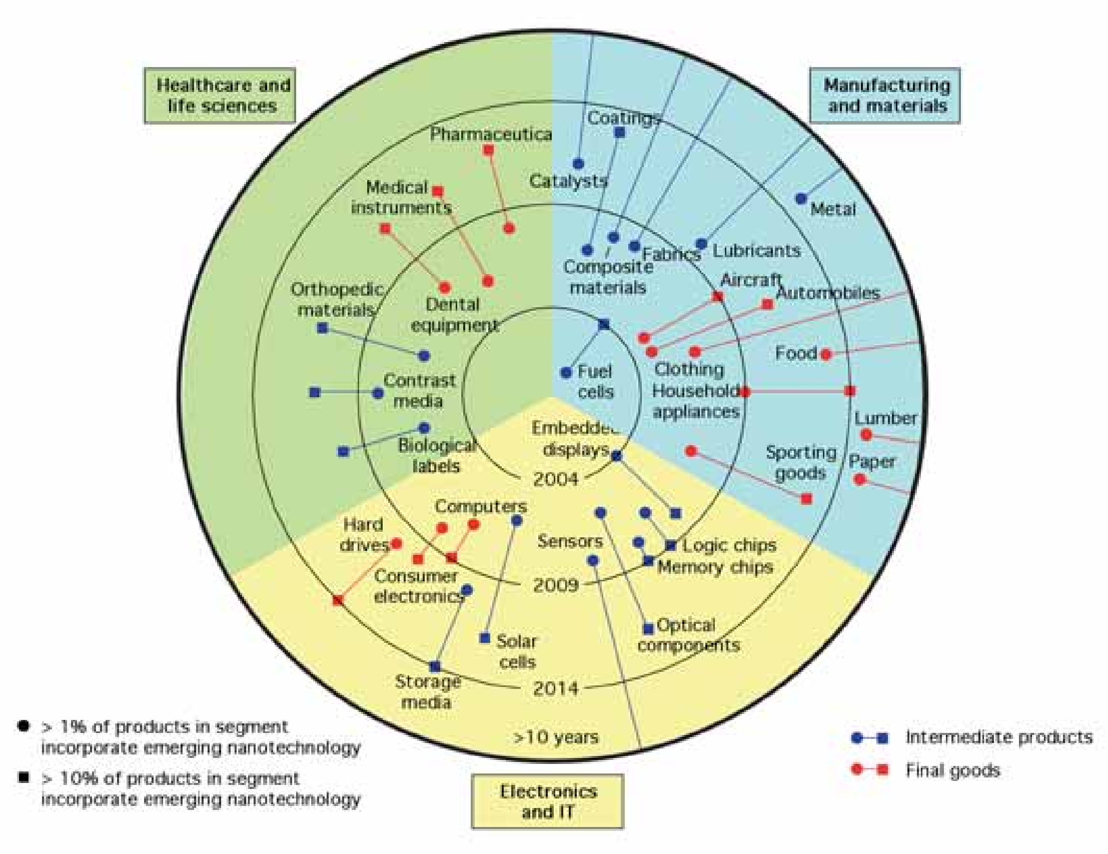
- micro invasive devices; micro life, lab-on-chip
- distributed sensor and actuator systems; autonomous sensors for harsh environments
- smart microchannel technology; modeling and design of microsystems
- microsatellite
- microfactory

The Holst center was founded in 2005 by IMEC (B) and TNO (NL) in order to valorize nano- and microsystems technology into innovative products. It has two technology programs:

- system in a package: wireless, autonomous sensors
- system in a foil: flexible electronics in a foil for lighting, sensors, tags and energy

The center has received a 50 MEuro grant from the Ministry of Economic Affairs. It is an open innovation center and industrial partners can sign in and participate in the technology programs.

Expectations on nanotechnology deployment by sector



from Institute for Defense Analysis (IDA, Washington)

04. When will nanotechnology be available

Although several applications of nanotechnology already exist in our daily life, we believe that the vast majority of new innovative products and applications enabled by nanotechnology are still hidden in the future. Examples of currently deployed nanotechnology products are:

- nanoelectronics, processor chips, high density memory, CCD chips (Moore's law), opto-electronics
- MEMS devices such as ink-jet printheads, pressure and flow sensors, inertial motion units
- DNA biochips, membranes, fuel cell components
- nanosized pigments and additives (UV-blockers) in paints, coatings, lubricants and cosmetics
- nanoclay reinforced materials

With the growing number of nanotech research groups and growing worldwide R&D budget, the number of nanotechnology developments has increased enormously with a subsequent growth and broadening of the potential nanotech product portfolio. Future nanotechnology products are expected to arise in the following areas:

- RFID-tags with nanosensors: sensortags
- µ-power
- distributed, wireless, autonomous sensors
- adaptive materials with built-in sensors and actuators
- nanobio, nanowire and biotransistors
- nanomedicine

The area is so large now that sub-areas have been formed such as nanoelectronics, nanomedicine, nanobio, nanomaterials, nanofibers, nanosensors, nanomachines, nanobots and many more. Some examples of these sub-areas are reviewed in the appendix. By fusing nanotechnology with other technologies such as bio, the R&D nanoworld is expanding rapidly in many directions.

Technology radars

One way of ordering and structuring this nanolandscape is to plot technology radars. Technology radars are radial plots with the radius as timeline, usually 15 or 20 years, towards market readiness. The radar circle can be divided into three or four segments covering the following application domains:

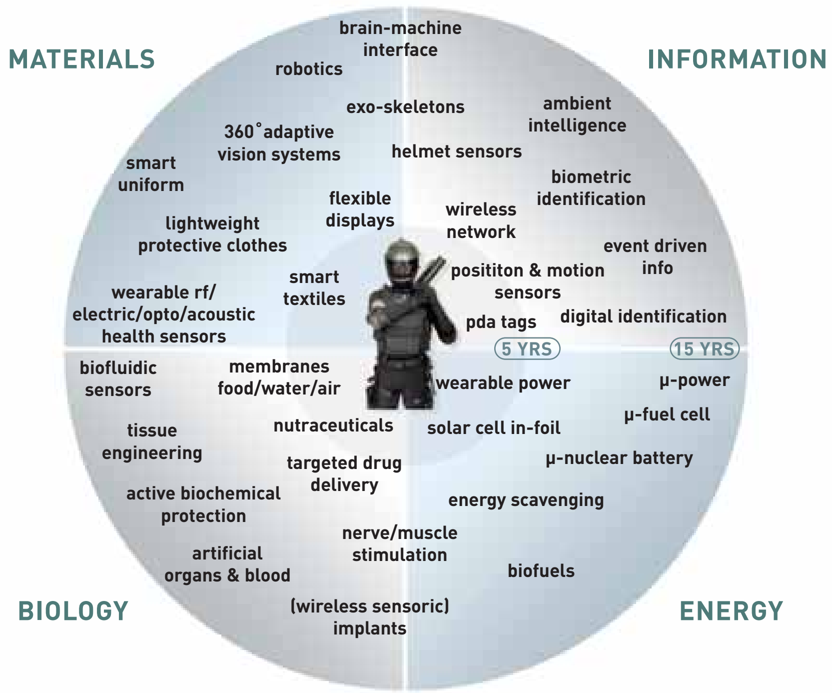
- ict, information and communication
- energy or power
- bio and life science
- materials and manufacturing

In this chapter nanotechnology radars are being proposed for eight application domains in both the military and civil world:

- human centric: soldier, first responder, medical, sport
- vehicles: land vehicles, automotive
- marine: naval, maritime
- aerospace: missiles, fighters, aero planes
- space: satellites
- weapons and law enforcement
- logistics
- security and surveillance

Human centric

- Self supporting
- Connectivity
- Mobility
- Ambient intelligence



Technology radar

Human centric systems are in development in order to secure and optimize human performance and well-being. The systems provide monitoring and feedback functions of the human being in its environment plus protection and support tools. This approach is seen in top sport, medical care, revalidation, first responders, firefighters, police and the military. For military applications it enables better survivability, self-supporting ability and mobility, improved group tactics and information intelligence. In practice such systems result in the ability to participate in a mobile information network, the use of more comfortable, protective and functional suits, wearable intelligence such as sensors and displays for situational awareness and body condition monitoring. Nanotechnology is here crucial. Without miniaturisation such functionalities cannot be adapted to lightweight, wearable systems.

Materials

Nanotechnology enables high strength, durable, sensoric and active materials. Nanostructures and nanocomposites are in development for the following functionalities:

- lightweight protective clothes: flexible antiballistic textiles, self BC decontaminating nanofiber fabric
- adaptive suits: switchable fabrics for improved thermal control, switchable camouflage
- microsensors for body & brain sensing, environmental and situational awareness, to be integrated into a smart suit or a smart helmet
- wearable and/or flexible displays for visual feedback
- auxiliary supports: flexible/rigid textiles for additional strength, exoskeletons and robotics to assist the human tasks

Information

In order to operate in a safe and secure wireless network, the human being will be equipped with:

- miniaturised hardware: sensors, readers, displays and radio transmitters, some of these already present in PDA's and mobile phones
- personal secured access to equipment (biometric id) and information (digital id)

Energy

With the increase in wearable functionalities and electronics, the need for lightweight wearable electric power is very critical. The following developments are present:

- flexible solar cells to recharge batteries
- µ-fuel cell, preferably to be operated by diesel or biofuel (e.g. sugar)
- µ-nuclear battery for long endurance
- energy scavengers, e.g. electricity from vibrations, for low power applications

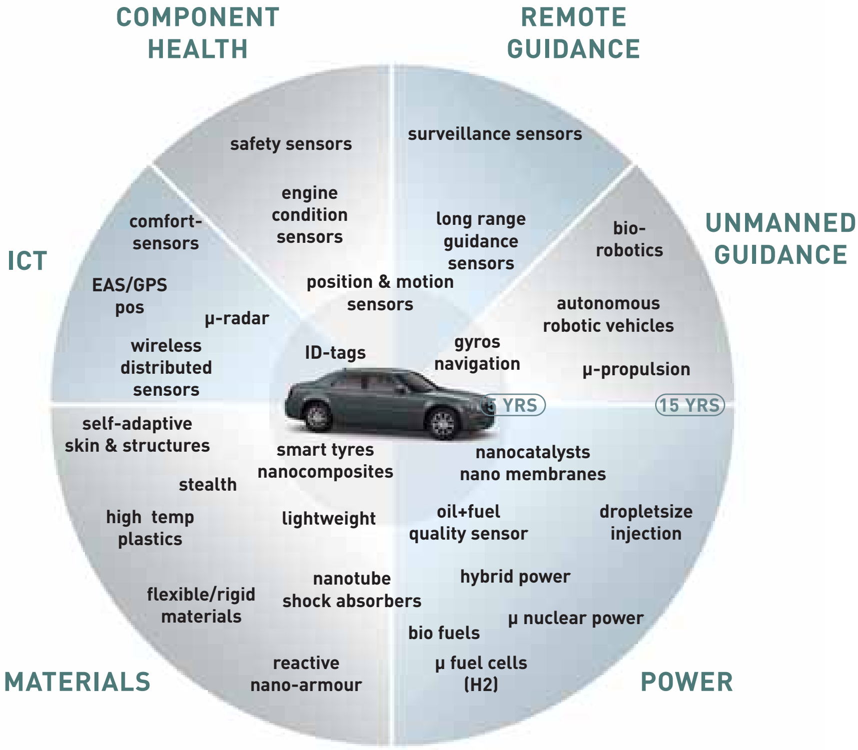
Bio

The nano-bio fusion is a booming area with high expectations that major steps in health treatment, body repair and body improvement can be made. It is regarded as the most innovative domain of this moment. Developments are in the field of:

- nanomedicine: targeted drug delivery by medically functionalized nanoparticles, for rapid cure without side effects or human stimulation
- regenerative medicine: DNA programmed tissue engineering for quick and efficient wound healing, rebuilding of organs and other body parts
- smart implants: biocompatible implants that can sense and actuate in order to repair or enhance a body function

Vehicles

- Lightweight
- Multi-purpose
- Intelligence-guided
- Protection
- Low energy
- Comfort



Technology radar

Future vehicles are expected to be lightweight, multipurpose, intelligence-guided, low in energy consumption, safe and protective for the passengers and highly comfortable. This applies both to civil automotive vehicles as well as for military land vehicles. Military vehicles have additional requirements with respect to armour protection, specific detection and surveillance sensors and weapon systems.

Materials

Nanotechnology enables the following material functionalities:

- lightweight: high strength nanocomposite plastics are expected to replace metal and thus reduce weight and radar signature
- smart components: components with built-in condition and load monitoring sensors, in the long term: self-repairing or self-healing materials
- adaptive structures: active structures that adapt to changing conditions such as adaptive camouflage, suspension, flexible/rigid etc
- stealth: radar absorption coatings, camouflage
- armour: nanoparticle, nanofiber reinforced antiballistic structures, reactive nanoparticle armour, shock absorbing nanotubes

ICT

Vehicles are expected to be equipped with the following ICT features:

- position sensing and signaling: GPS for navigation and with EAS for tracking and tracing vehicles
- identification: RFID - tags for remote identification
- security:
  - radar
  - bolometer (infrared) for surveillance
  - acoustic arrays for sniper detection
- wireless networks: vehicle internal sensoric network will become wireless; connection to distributed external network
- directional RF communication: micro antenna arrays enable directional radio communication with reduced power and signature

Remote and unmanned guidance

With nanotechnology advanced sensor and wireless communication capabilities are becoming possible, e.g. via distributed ad-hoc sensor networks, enabling long range guidance of all kinds of vehicles. Advanced intelligence can be built-in thanks to the expanding µ-sensor capabilities, integration of sensor functions and information processing power. Especially for military use, continuous effort is put in the development of unmanned and autonomous vehicles e.g. for surveillance. Nanotechnology is crucial here to minimize size, weight and power consumption, important for long range coverage.

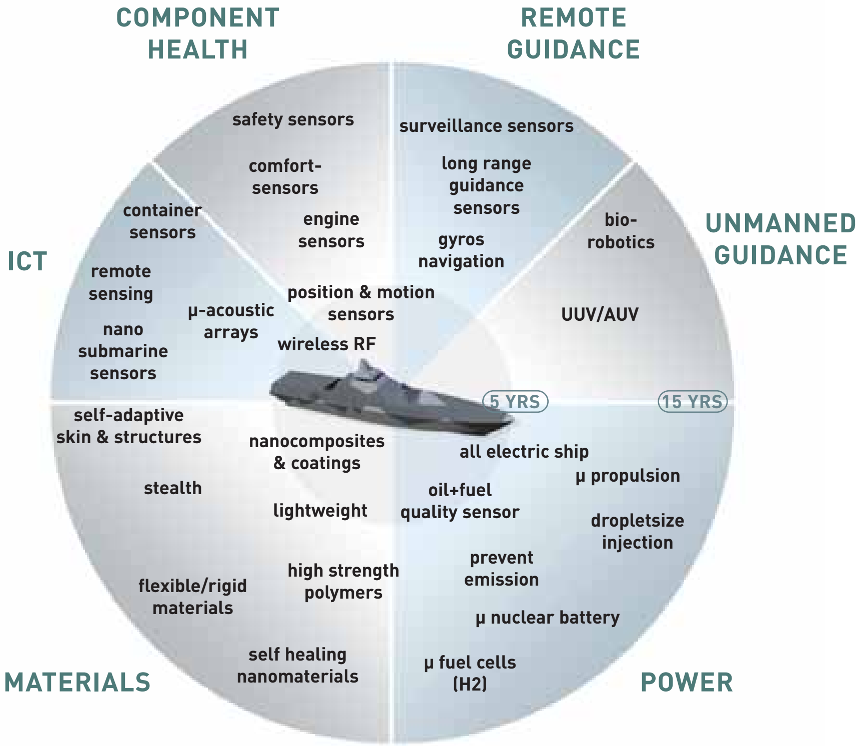
Power

Focus is on lightweight and energy-efficient powering. Reduction of thermal, radar and acoustic signature is an additional aspect for the military. Main developments are:

- hybrid, electrical/combustion, powering, driven by civil automotive, reduces consumption and signature
- hydrogen fuel cell, preferably with diesel or biofuel (e.g. sugar) as hydrogen source via microreactor conversion
- for miniaturised, unmanned vehicles: µ-fuel cell, µ-nuclear battery

Naval vessels

- Lightweight
  - materials
  - small components
- Intelligence-guided
- Protection / safety
- Low energy
- Comfort



Technology radar

Future vessels are expected to be lightweight, intelligence-guided, low in energy consumption, safe and protective for the passengers and high in comfort. Also onboard intelligence will continuously increase, facilitating automated control and maintenance. Naval vessels have additional requirements with respect to detection and surveillance sensors and weapon systems.

Materials

Nanotechnology enables the following material functionalities:

- lightweight: high strength nanocomposite plastics are expected to replace metal and thus reduce weight and signature
- smart components: components with built-in condition and load monitoring sensors, on long tern self repairing, healing materials
- adaptive structures: active structures that adapt to changing conditions such as adaptive aqua dynamics, flexible/rigid etc

ICT

Vessels are expected to be equipped with the following ICT features:

- position sensing and signaling: GPS or underwater acoustics for navigation, with eas for tracking and tracing
- identification: RFID - tags for remote identification
- security: μ-radar and μ-acoustic arrays for surveillance

Remote and unmanned guidance

With nanotechnology advanced sensor and wireless communication capabilities are becoming possible, e.g. via distributed ad-hoc sensor networks, enabling long range guidance of all kinds of vehicles. Advanced intelligence can be built-in thanks to the expanding μ-sensor capabilities, integration of sensor functions and information processing power. Especially for the military use, continuous effort is put in the development of unmanned and autonomous vessels e.g. for surveillance. Nanotechnology is crucial here to minimize size, weight and power consumption, important for long range coverage.

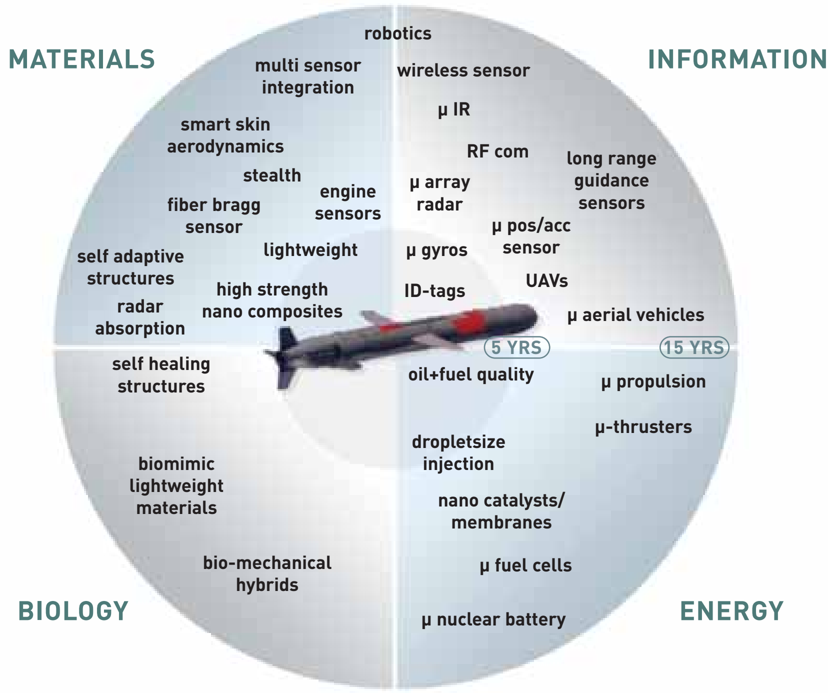
Power

Focus is on lightweight and energy-efficient powering. Reduction of thermal, radar and acoustic signature is an additional aspect for the military. Main developments are:

- all-electric vessel enabling very low signature
- hydrogen fuel cell
- for miniaturised, unmanned vessels: μ-fuel cell, μ-nuclear battery

Aero-nautics

- Lightweight
- Safety
- Intelligence-guided
- Protection / comfort
- Low energy
- High speed
- Adaptive



Technology radar

Future fighters and missiles are expected to be lightweight, intelligence-guided, low in signature, high speed and maneuverable. The onboard intelligence will continuously increase, facilitating automated control and maintenance. Special attention goes to specific detection and surveillance sensors and weapon systems.

Materials

Nanotechnology enables the following material functionalities:

- lightweight: high-strength nanocomposite plastics and biomimic (human bone type) structures to reduce weight and radar signature
- smart components: components with built-in condition and load-monitoring sensors, such as fiber bragg, in the long term self-repairing, self-healing materials
- adaptive structures: active structures that adapt to changing conditions such as adaptive aerodynamics, adaptive skin
- stealth: radar absorption coatings, thermal camouflage
- high-energetic propellants: e.g. nano-dispersed aluminum as propellant agent

ICT

Aeronautic vehicles are expected to be equipped with the following ICT features:

- position sensing and signaling: GPS for navigation, with EAS for tracking and tracing
- identification: RFID tags for remote identification
- security and guidance: µ-radar, µ-bolometer (infrared) and µ-acoustic arrays

Remote and unmanned guidance

With nanotechnology advanced sensor and wireless communication capabilities are becoming possible, e.g. via distributed ad-hoc satellite networks, enabling long-range guidance. Advanced intelligence can be built-in thanks to the expanding µ-sensor capabilities, integration of sensor functions and information-processing power. Especially for the military, continuous effort is put in the development of unmanned and autonomous flying platforms e.g. for surveillance. Nanotechnology is crucial here to minimize size, weight and power consumption, important for long range coverage.

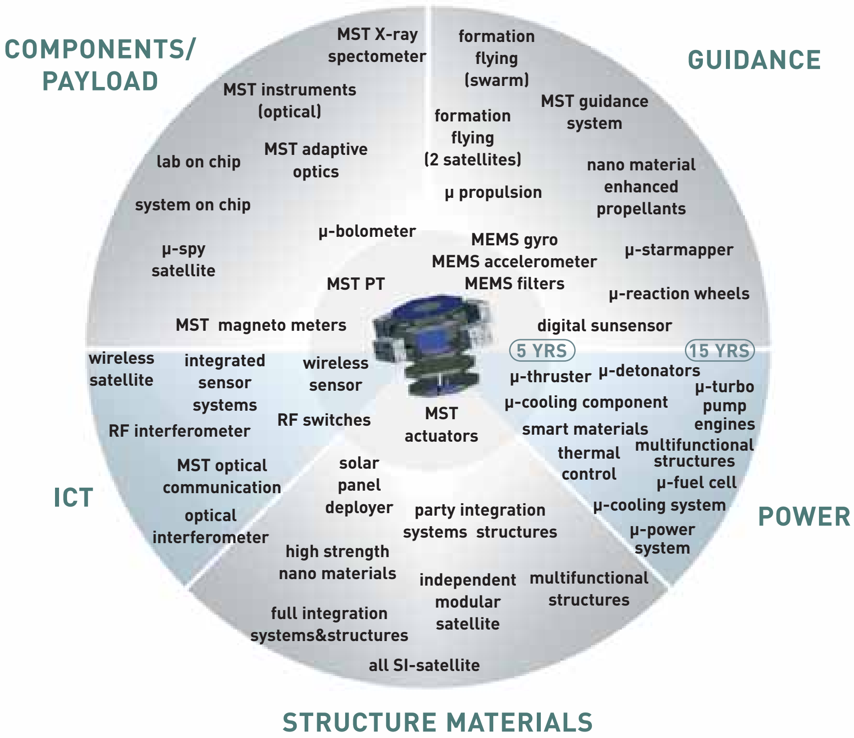
Power

Focus is on lightweight and high-energy powering. Reduction of thermal signature is an additional aspect for the military users. Main developments are:

- nanocomposite energetic materials
- for miniaturised, unmanned vessels: µ-fuel cell, µ-thrusters, µ-nuclear battery

Satellites

- Lightweight
- Distributed & redundant systems
- Wireless
- High integration of systems
- Low power
- Many small vs. one big



Technology radar

As a reaction to the reduction of budgets in the 1990's, the space industry has focused on smaller, lighter, more intelligent space systems that will achieve reduced total mission costs and more payloads. Smaller satellites are becoming feasible thanks to the miniaturisation enabled by nanotechnology. Besides reducing their size, weight and power consumption, the use of micromachined devices could give better component integration in areas such as propulsion, communication, data processing, power generation and navigation. With a distributed network of small satellites instead of one big one, both functionality (multi aperture synthesis for better accuracy, formation flying) as well as redundancy is gained. The following classification exists:

- minisatellite 50 – 500 kg
- microsatellite 10 – 50 kg
- nanosatellite 1 – 10 kg
- picosatellite < 1 kg

Materials

Nanotechnology enables the following material functionalities:

- lightweight: high-strength nanocomposite plastics and biomimic (human bone type) structures to reduce weight
- smart components: components with built-in condition and load-monitoring sensors, such as fiber bragg
- adaptive structures: e.g. adaptive skin for better thermal control
- high-energetic propellants: e.g. nano-dispersed aluminum as propellant agent

Payload

All components in small satellites and satellites at micro scale need to be transformed and integrated into microsystems. This accounts for:

- radio communication, position and motion sensors, guidance sensors
- µ-instrumentation: x-ray, infrared, optical and rf interferometry, mass spectrometers, lab-on-chip
- security and guidance: µ-radar, µ-bolometer (infrared) and µ-acoustic arrays

Power

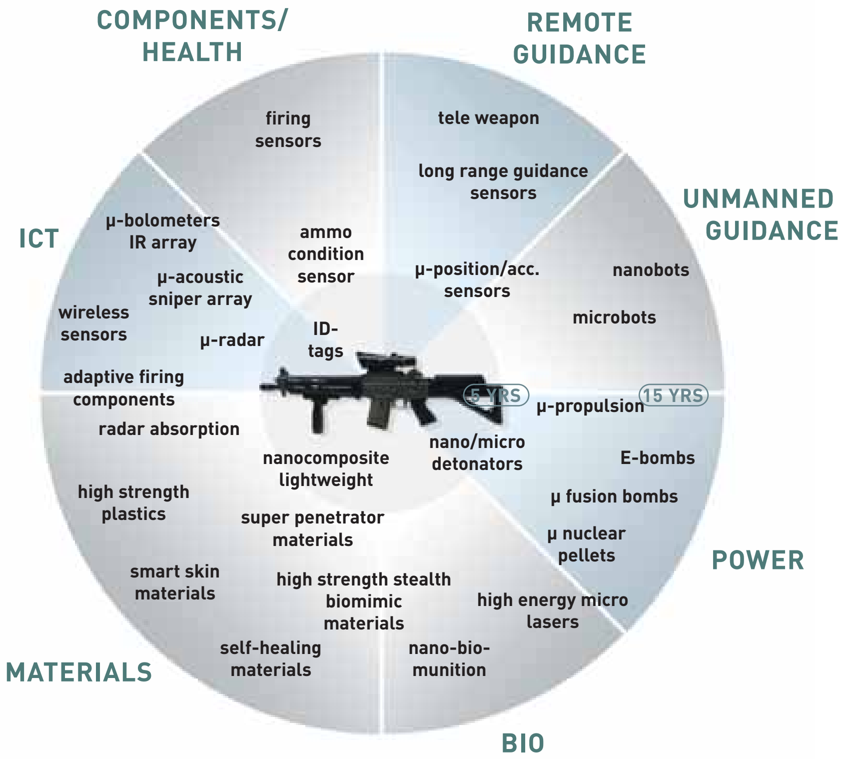
Focus is on lightweight and high energy powering. Main developments are:

- nanocomposite energetic materials
- lightweight, flexible and efficient photovoltaic solar cells
- for mini- to picosatellites: µ-fuel cell, µ-thrusters, µ-nuclear battery

The ultimate goal is to develop a complete satellite-on-chip, the so-called picosatellites. Microsatellites (appr. 10-30 cm) are in development in many countries: USA/NASA, UK, France, Germany, Sweden, Spain both for civil and defence applications.

Weapons

- Lightweight
- Safety
- High impact
- Intelligence-guided
- Low energy
- High speed
- Adaptive



Technology radar

Developments in weapon technology take place both in the direction of more lethal as well as non-lethal weapons. For lethal weapons the focus is on precision targeting, minimum weight and signature, optimal impact damage. Cheap, onboard intelligence is needed. Non-lethal weapons, to neutralize the enemy temporarily, are relatively new and evolving. They usually make use of energy waves in different forms, directed by array technology. Non-lethal weapons are also of interest to civil security services and the police.

Materials

Nanotechnology enables the following material functionalities:

- lightweight: high strength nanocomposite plastics and biomimic (human bone type) structures to reduce weight and radar signature
- smart components: components with built-in condition and firing monitoring sensors, such as fiber bragg
- adaptive structures: active structures that adapt and correct firing conditions
- super penetrator materials: nanostructured cone material that sharpens upon impact or gives additional damage
- high-energetic propellants: e.q. nano-dispersed aluminum as propellant agent

ICT

Weapon systems are expected to be equipped with the following ICT features:

- sensors: µ-radar, µ-bolometers (infrared) and acoustic arrays for better targeting guidance, condition sensors for weapon and ammo
- identification: rfid tags, personalized biometric access

Remote and unmanned guidance

With nanotechnology advanced sensor and wireless communication capabilities are becoming possible, e.g. via distributed ad-hoc distributed sensor networks. This enables new functionalities:

- teleweapons: expanding sensor capabilities and wireless communication enables remotely operated weapons
- self-adaptive targeting: based on feedback from previous impacts
- nano and microbots: miniaturised, autonomous or remote controlled robotic systems with firing capability

Power

Next to high-impact weapon systems, non-lethal weapons are in development in order to neutralize target groups for a certain time. This is also of interest to civilian law enforcement. Nanotechnology is important to reduce size and weight making these systems suitable as personal weapons. This accounts for:

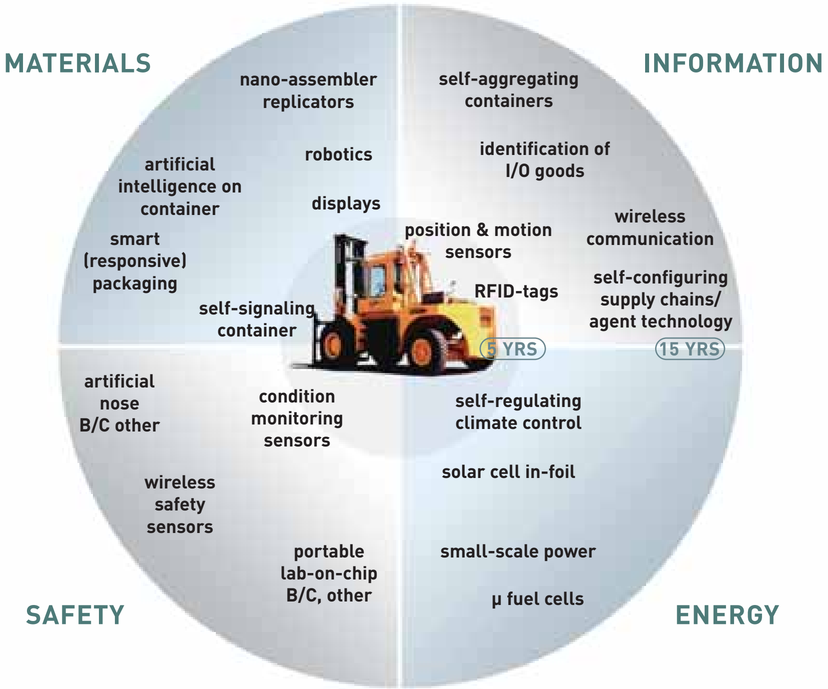
- non-lethal high-energy µ-lasers, microwave, RF or acoustic waves generators

For high-impact ammunition, nanotechnology can be used for the following developments:

- high-energetic nanocomposite materials
- µ-fusion bombs, µ-nuclear pellets

Logistics

- Speed
- Safety
- Unmanned
- Self-aggregating
- Responding/ smart



Technology radar

Technologies for logistics seem to be focussed on two major issues: how to increase the security and safety of transported goods and secondly how to improve the speed and efficiency of the logistic chain. Logistics gets more and more involved with high-tech systems such as unmanned operations, automated guidance, ict, identification for tracking, tracing and security. Also the condition and health monitoring of goods during transportation and storage is becoming an issue.

Materials

Nanotechnology can offer logistics the following advantages:

- lightweight containers: especially nanocomposite plastics, shock-absorbing materials
- self-signaling containers: smart materials or sensors to alarm for mechanical or chemical deficiencies, displays function
- nano-assemblers that can replicate products: would reduce logistics, at this moment still fiction

Information

ICT sytems are used for tracking and tracing as well as for security reasons:

- positioning: miniature GPS modules
- identification: RFID, in the future coupled to sensor tags
- condition and health monitoring: wireless sensor tags to monitor and log mechanical, thermal and chemical loads
- self-aggregating containers: integrated robotic systems with autonomous logistic handling, futuristic long term development

Energy

Future packaging and containers will need on-board power for electronic and other functionalities. Options are:

- micro or miniature power (combustion) engines
- micro or miniature cooling and climate control devices
- (flexible) solar cells to recharge batteries
- μ-fuel cell, preferably to be operated by diesel or biofuel (e.g. sugar)

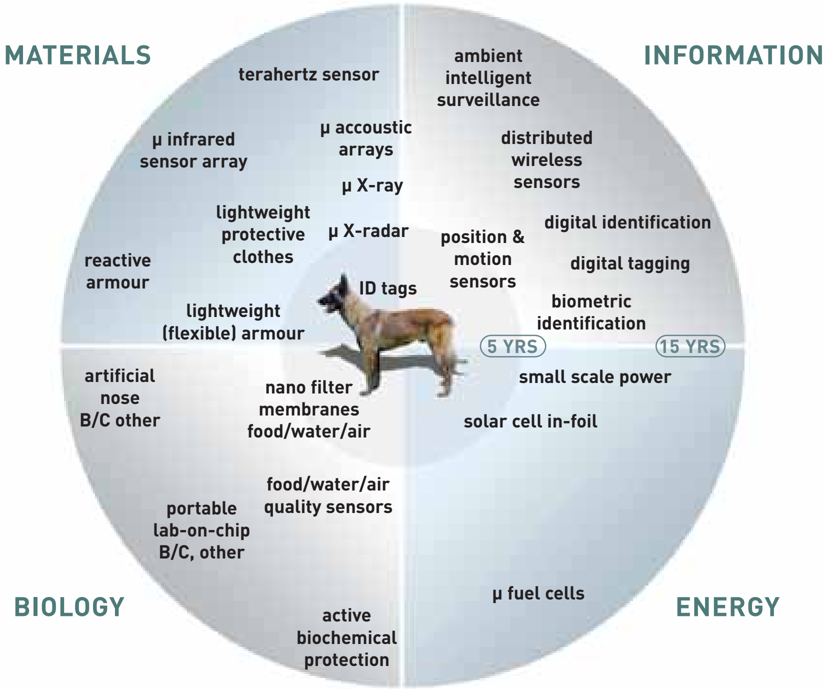
Safety

The safety of packaged and transported goods can be monitored with upcoming microsensors:

- (wireless) sensor tags that monitor mechanical and temperature loads
- artificial electronic nose to detect gases and vapors
- lab-on-chip systems to detect bacterial or chemical decontamination

Security

- Bio-chemical-radiological
- Explosive detection
- Automated scene understanding
  - Optical/infrared/ terahertz
  - Acoustical
  - Radar
- Infrastructure protection
- Physical security



Technology radar

Both for social and national security reasons, technologies are in development that enable early detection of (potentially) hazardous conditions, goods and human behavior. Sensing and detection, surveillance, situational awareness, interpretation, automated scene understanding are crucial aspects.

Materials

Nanotechnology-related material developments are in the field of:

- lightweight protective clothes
- antiballistic and shatterproof armour
- advanced sensors: high-resolution vision systems, RF, infrared, acoustic arrays, terahertz & through-the-wall radar vision

Information

ICT technology is quite dominant in security systems and will further expand in the future:

- tags: physical identification tags (RFID) for goods, digital ID tags for documents and information
- biometric sensing for personal identification: fingerprint, face recognition, DNA identification
- ambient intelligence for surveillance: by means of distributed wireless sensor networks
- tracking & tracing with position and motion sensors

Energy

Mobile security systems will need on-board power for electronic and other functions. Options are:

- miniature power (combustion) engines
- (flexible) solar cells to recharge batteries
- µ-fuel cells, preferably power by diesel or biofuels
- energy scavengers for low power distributed sensor networks

Biology

Microtechnology is in development to detect early hazardous conditions for the human biosystem

- artificial electronic nose to detect gases and vapours
- lab-on-chip systems to detect bacterial or chemical decontamination in air, water and food
- B/C protection with catalytic nanofiber structures for filtering and decontamination

Future bionanosensor array for BC plus visual alarm (illustration MIT/ISN)

While nanotechnology is in the “pre-competitive” stage, meaning its applied use is limited, nanoparticles are already being used in a number of industries. Nanoscale materials are used in electronic, magnetic and opto-electronic, biomedical, pharmaceutical, cosmetic, energy, catalytic and materials applications. Areas producing the greatest revenue for nano-particles reportedly are chemical-mechanical polishing, magnetic recording tapes, sunscreens, automotive catalyst supports, biolabelling, electro-conductive coatings and optical fibers. Source: NNI

The military use of nanotechnology should lead to higher protection, more lethality, longer endurance and better self-supporting capacities of future soldiers. Nanoresearch for defence can be variously divided into different categories.

Nanoresearch for defence in the US can be divided into six categories:

- nano-assembly of materials and parts
- nano-optics
- nanochemistry
- nano-electronics
- nanomechanics
- nanomaterials

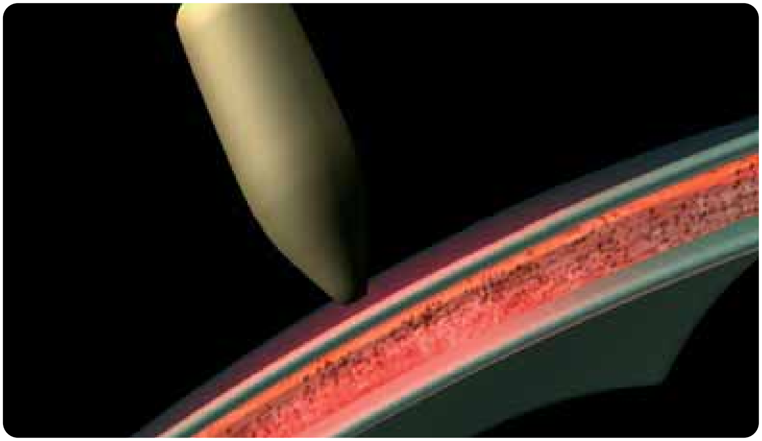
Another main division of nanotechnologies for defence is (see appendix):

- nano-electronics
- nanosensors
- structural nanomaterials (reinforced materials)
- nanofibers and nanoparticles

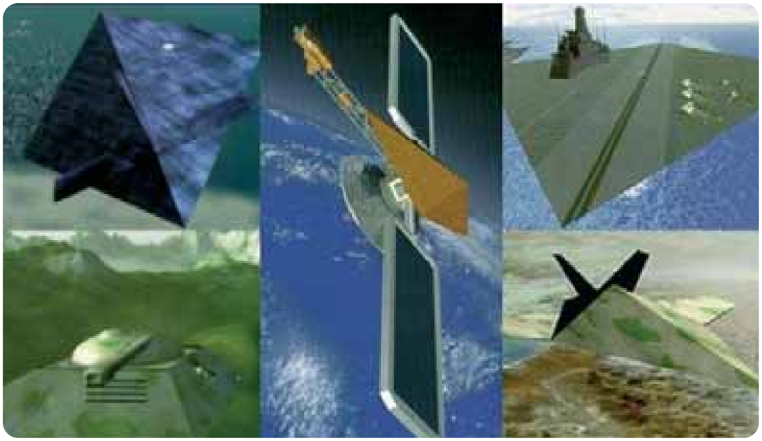
Nanotechnology for defence applications seems to concentrate mainly on five areas according to NRL:

- the future warfighter or combat soldier
- information dominance
- weapons of mass destruction: CBNRE
- weapons / countermeasures
- platforms

Technological innovations in these five areas will provide the basis for the future defence capabilities.



Future liquid nanoarmour with magnetic rheofluid (illustration MIT/ISN)



Future platform systems (illustration Boeing)

The future warfighter needs nanotechnology to reduce the weight per unit or per volume unity and needs lower electric power demand per specific function. He can use the properties of nanoparticles or nanofibers to create a large surface area (for sensors, absorption). Furthermore he will make use of more multi-functional structures in the future with mechanical, opto-electric, chemical and biological functions and he will have a biotic/abiotic interface between body and equipment. The future combat soldier should be self-supporting, highly lethal, equipped with additional and supportive intelligence, protected against all kinds of impacts (ballistics, bioagents, chemical agents). Nanotechnology will probably lead to solutions in the areas of body armour, insulation and ventilation, camouflage (IR, visible), integrated sensing devices and enhanced body monitoring and care systems.

Information dominance

Nano-electronics will lead to a lower power consumption per process on microchips, to a better signal transduction (signal to noise ratio will be improved), to higher processing speeds and shorter transit times and to a higher function density. Dominance on informatics and information control technology can thus be reached by developing and using nano-electronics for devices with high computing power at small-scale and low-power consumption (for sensor networks, artificial intelligence, brain-machine interfaces etc.) and micro- or nanosensor arrays for fast recognition of NBC threats on the battlefield by soldiers and sensor networks. Some people expect that with the coming of future generations of nano-electronics it will be possible to make an artificial version of the human brain within 100 years. This could have dramatic impact on the military operation as well as on industrial activities and civil tasks (James Murday, March 2004).

CBNRE-sensors

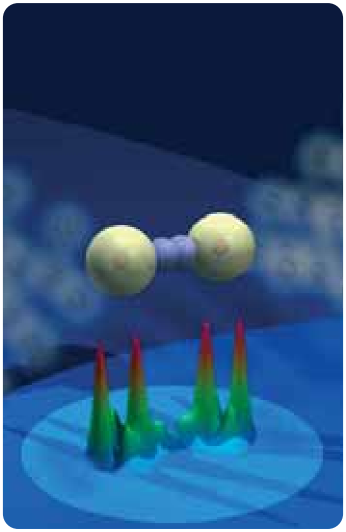
Nanotechnology is needed for improved detector sensitivities (signal to noise ratios), to miniaturize sensor arrays for selectivity, to tailor-make high-surface area materials for detection / absorption / deactivation and to create selective catalysts. Microsystems technology and nanotechnology will therefore enable small portable sensor systems capable of identifying Chemical, Bio, Nuclear, Radiation or Energy threats. This will enhance the flexibility of deployment, operations and increase the safety of soldiers and civilians and will enhance the environmental security.

Weapons / countermeasures

Nanomaterials can create a better control of energy release and can create shorter diffusion paths for high-intensity energy blasts. They will improve the grain-boundary effects on a mechanical level. Nanoparticles in or on materials can result in sophisticated scattering of visible and infrared light, enabling stealth functionality. Nanocomposites, consisting of nanoparticles dispersed in materials create a higher design and construction flexibility for weapons, platform systems etc. Nanostructured metals and particles can be used to create new uranium like high-penetration materials (source ARL), more controlled energy release in explosives and thrust-fuel systems, and new types of weapons (non-lethal, tailored explosives).

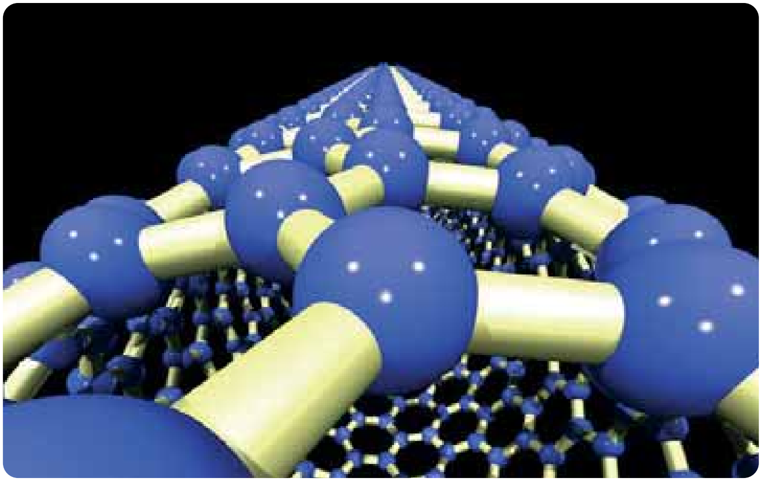
Platforms

For platform systems such as land vehicles, naval vessel, aeroplanes, nanotechnology can deliver a higher design flexibility, enabling multifunctional, adaptive structures, a controlled energy release and by integration of nanomaterials platforms will have increased functionality (integrated sensors, higher performance, adaptive skin structure). They will be nearly invisible for radar, IR and optical camera, will have reduced weight and will therefore be more lethal and more capable of gathering intelligence.



H2 Hydrogen image, Leiden Univ

Nanorobot, illustration NASA



Carbon nanotube illustration, Chris Ewels

Criteria for evaluation of impact on defence operations

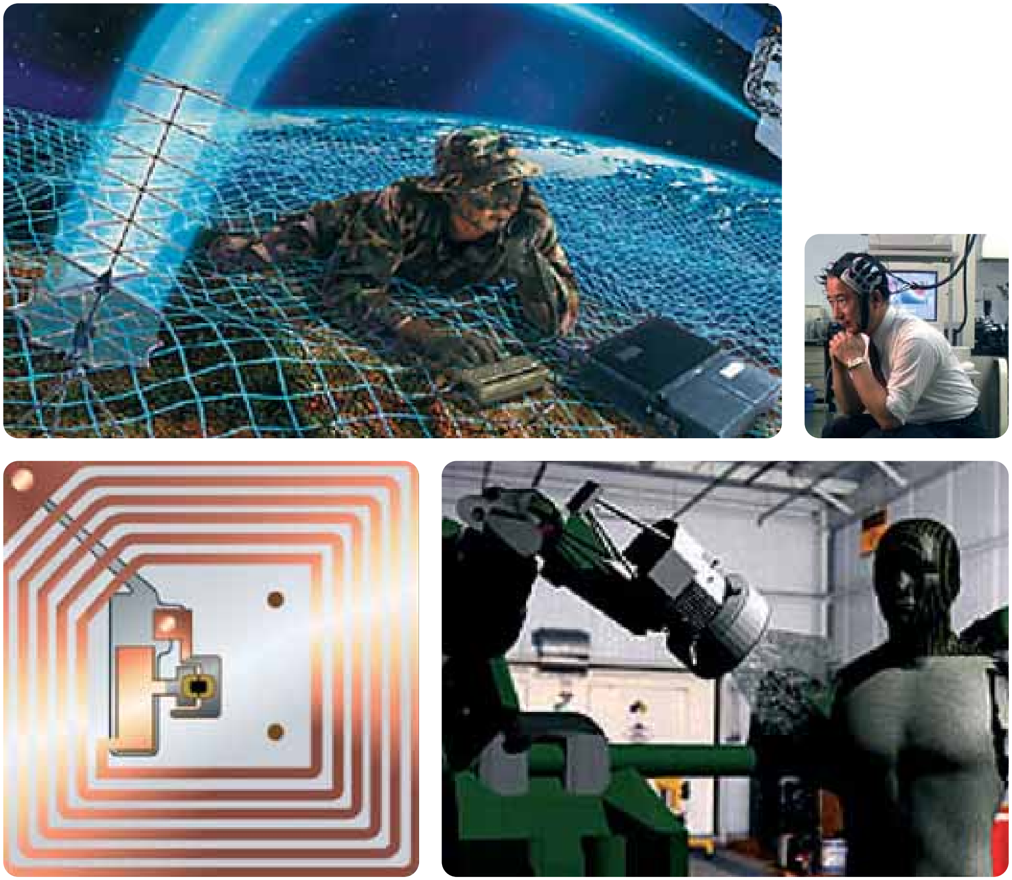
The impact of nanotechnology on future combat systems or military platforms depends largely on the criteria that the military commands require for future warfare operations. In this respect, the following criteria are distinguished:

- highly flexible deployability and mobility (low weight, fast deployment)
- effective engagement (high lethality)
- effective intelligence (acquire data on battlefield, operations area)
- logistics sustainability
- survivability and force protection
- command, control, communication (C3)
- endurance (self-supporting soldier).

Military strategists in the US consider nanotechnology to be the key technology to retain the military supremacy of US forces in the 21st century (source Rathenau Instituut). The main focus of US research is on the protection, the performance and survivability of the individual soldiers. The soldier is one of the main platforms of combat systems which could benefit from nanotechnologies which are being developed. The soldier system is also the central combat platform of future warfare approaches (centric warfare) and is connected to other platform systems (land vehicles, UAV's), and wireless sensor network system, the logistic supply chain, the paramedics and the central command.

Related civil developments that will boost nanotechnology: In the civil world nanotechnologies and microsystem technologies have been developed and implemented on a limited scale in cosmetics (creams, anti-sunburn lotions), automotive parts (catalyst systems, nanoparticles in tyres, pressure-, inertia- and airbag sensors), electronics industry (displays, sensors) and the life sciences industry. Some examples of technologies being developed and/or in use are:

- wireless μ-sensors (3D nano-electronics) and RFID tags (small, low power, use of polymer electronics)
- lab-on-chip DNA arrays, sample preparation systems for rapid biochemical analysis
- nanoparticles and nanofibers for nanocomposites (structural improvement of properties)
- drug delivery systems (packaging of medicine and food in nanoparticles, controlled release in body)
- health-monitoring systems and in-vivo body-sensing devices
- nanowires for use as sensors, transistors in next generation CMOS technology
- molecular electronics in the far future



From right to left: Network centric approach (US Army), brain-machine interface, RFID-tag (TI), spinning of nanofibers for future combat suit (Natick Soldier Center).

Based on the evaluation criteria for future defence operations and the current nanotechnology developments in the civil domain, a short list has been made of the most important nanotechnologies we now expect to have a foreseeable essential impact on future defence systems and applications.

These nanotechnologies are:

- **Tracking, tracing and remote identification systems via RFID tags (goods, vehicles, people):**
  Identify fellow and enemy soldiers via long-range RFID-systems, localize their positions, identify and localize goods and vehicles (logistic tracking & tracing), check ID, position and quality of preserved food packs. These RFID-tags can be passive (without power source) or semi-passive/ active (able to transmit information without interrogation), can have an incorporated sensor function and can possibly have a radar reflection characteristic for positioning and identification on large distances.

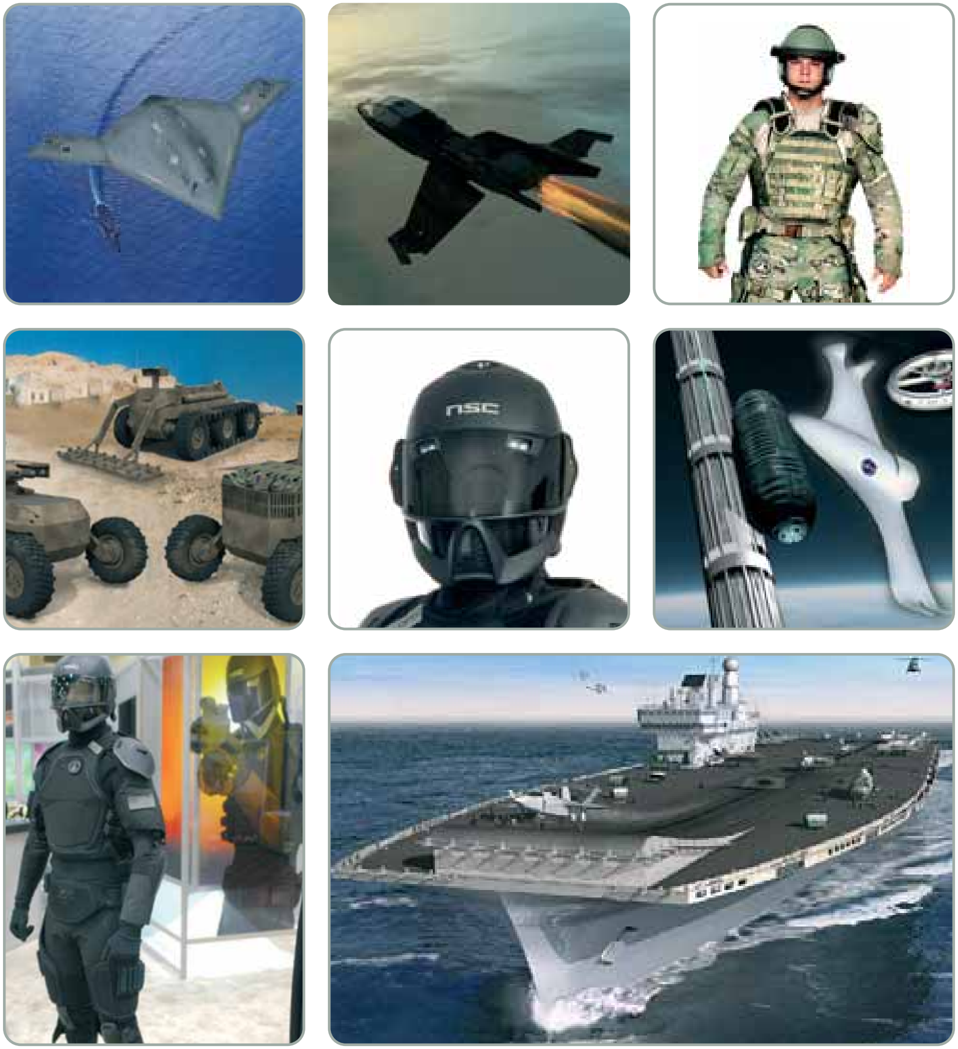
- **µ-power (necessary for future miniaturisation, portable power for the soldier):**
  Micropower systems can be used to power sensor systems in the combat suit, to recharge batteries of microsystems, to power communication and positioning systems, to power food preparation systems etc.

- **µ-vehicles & robotics, remote & autonomous:**
  These systems can be used to reduce the risk of manned patrol, reconnaissance and intelligence-gathering operations. The size and power consumption of the systems will get smaller in the future, resulting in small and micro nanosystems and later nanosystems which are redundant and can be replaced easily to continue with information gathering and other operations. Another aspect of these systems is the ability to identify fellow and enemy soldiers via sensor equipment. Furthermore we expect that brain-machine interfaces for remote control of platform systems and autonomously operating robotic systems will get more dominant in the next 15-20 years.

- **Wireless sensors, ambient intelligence for the soldier, network centric operations:**
  A distributed network of sensors can operate autonomously, be self-learning and self-responsive and will evolve into an ambient intelligence system reacting to other elements on the battlefield (soldiers, equipment, environmental influences etc.)

- **Smart structures:**
  Smart structures are structures consisting of a combination of more traditional materials and nanomaterials (nanoparticles, nanofibers) which can perform specific sensor or actuator functions, have a higher strength, give better protection levels and can be responsive or reactive to certain influences. Some examples of future smart structures are:
  - nanocomposites: high strength & temperature, lightweight, non-metal
  - biomimic structures: lightweight-bone type, self-healing/ assembling
  - integrated functions: adaptive, sensoric, actuating, (polymer) electronics
  - active coatings: adaptive, stealth, bio-active, flexible display

The key words for military applications are: smart structures, smart skin, smart uniform, smart textiles.



Future platform concepts (photos/illustrations: Wright Brothers Aeroplane Company, US Navy, Wallpaperworld, Lockheed Martin, BAE & Crown, NASA, USNI, US Army)

Based on the technology radars, the input of Dutch defence specialists and TNO's defence researchers a number of future platform concepts for the Dutch defence organisation have been created:

- wireless soldier
- smart uniform
- land vehicle
- weapon
- logistics
- micro vehicles/robots, UAV/MAV
- micro/small satellites

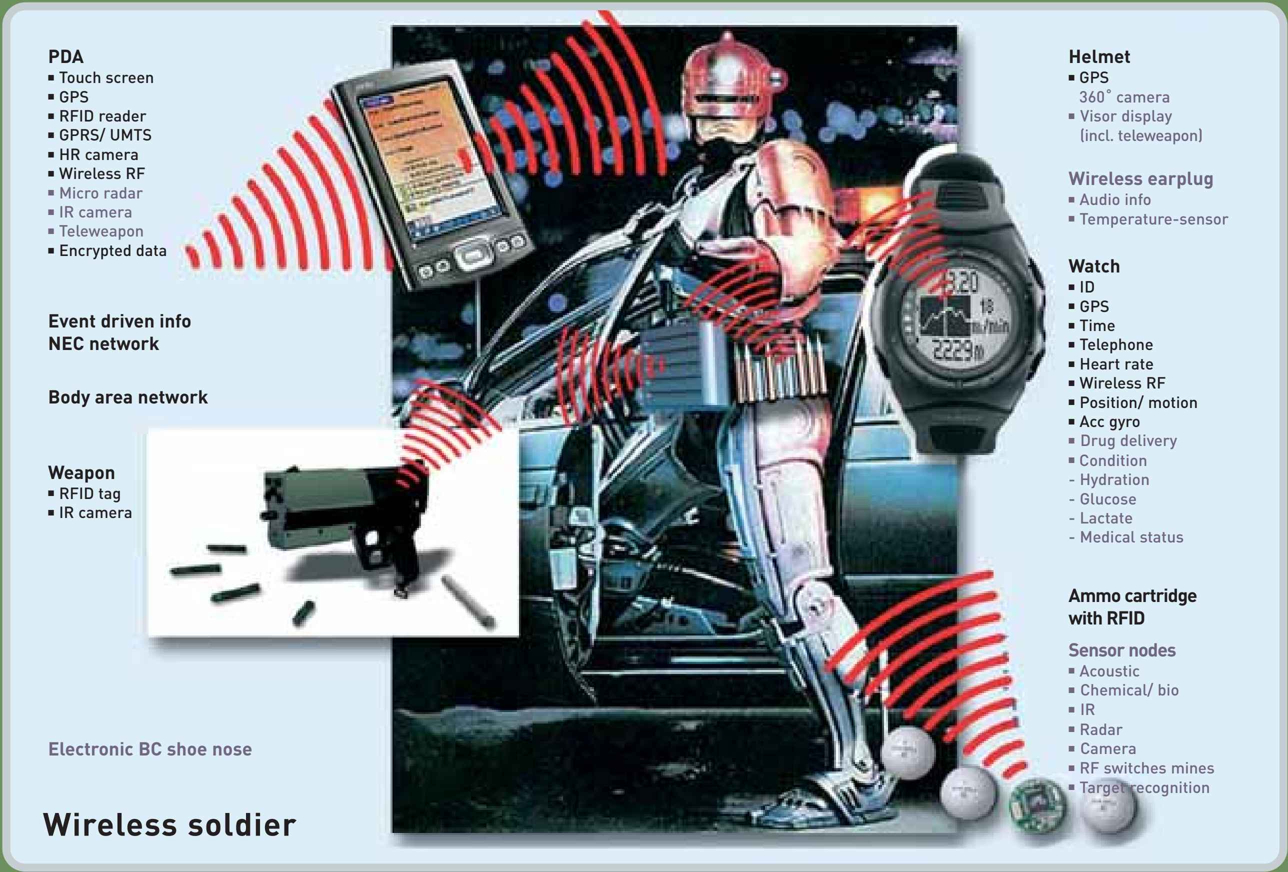
The platform concepts represent a first selection and integration of microsystem- and nanotechnologies which have significant importance for the Dutch defence organisation and which should either be researched and developed further or should be followed closely over the next years.

The wireless soldier in a smart uniform is a central element in the future combat system and he will be able to interact easily with the other platforms by means of the enabling microsystems and nanotechnology systems (soldier-centric approach).

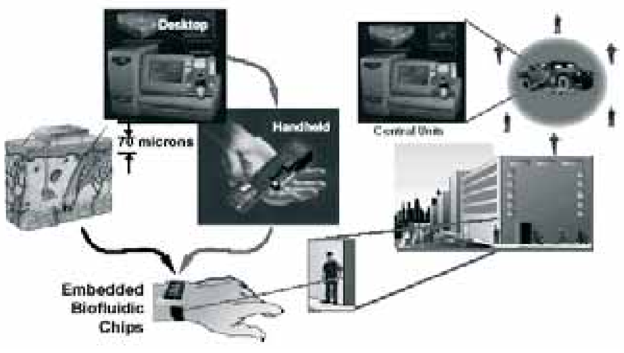
Key elements in the soldier-centric platform concepts (wireless soldier and smart uniform) are the protection of his body (body armour, camouflage, the monitoring and modification of body physiology, sensors, adapted temperatures around the body) and the ability to survive with portable power and preservation and preparations systems for food and water (nanofilters, anti-microbial release). His weapon system will also be automated and linked to his other personal devices.

The impact on land vehicles seems limited and consists mainly of integration of microsensor systems and the use of nanomaterials for structural components and armour plates. The impact of nanotechnology on manned or unmanned aerial vehicles and satellites will be significant. They can be drastically reduced in size and costs with the application of nanoelectronics, nanocomposites and adaptive materials.

Future logistic concepts will be impacted by microsystem-technology, by nanomaterials contributing to lightweight composite structures and reactive sensor systems.


PDA
▪ Touch screen
▪ GPS
▪ RFID reader
▪ GPRS/ UMTS
▪ HR camera
▪ Wireless RF
▪ Micro radar
▪ IR camera
▪ Teleweapon
▪ Encrypted data
Event driven info
NEC network
Body area network
Weapon
▪ RFID tag
▪ IR camera
Electronic BC shoe nose
Wireless soldier
Helmet
▪ GPS
360˚ camera
▪ Visor display
(incl. teleweapon)
Wireless earplug
▪ Audio info
▪ Temperature-sensor
Watch
▪ ID
▪ GPS
▪ Time
▪ Telephone
▪ Heart rate
▪ Wireless RF
▪ Position/ motion
▪ Acc gyro
▪ Drug delivery
▪ Condition
- Hydration
- Glucose
- Lactate
- Medical status
Ammo cartridge
with RFID
Sensor nodes
▪ Acoustic
▪ Chemical/ bio
▪ IR
▪ Radar
▪ Camera
▪ RF switches mines
▪ Target recognition

The future soldier-concept wireless soldier is equipped with a Body Area Network consisting of a number of wireless products communicating with each other: PDA/mobile phone, helmet / visor with head display, watch, weapon, supplies of cartridges, sensors on body or garment. All these systems can gather data, exchange data with each other and can give the soldier the essential info via his PDA, earplug, display, watch etc. The wireless soldier is connected via phone and PDA to the centric warfare system, his commander, the distributed sensor network on the battlefield and his fellow soldiers.
All technologies in black are available for integration within a period of 0-5 yrs, whereas the technologies in greyblue will become available in a timeframe of 10-15 years. Essential part of the wireless soldier is the ability to monitor his position, his physical and mental condition, supplies and status of equipment. His watch or other personal device (PDA/Phone/ Smart helmet) will have basic functions like positioning, wireless communication, RFID-reader, heartrate monitoring (wireless), accelerometers but in the future also enhanced body function monitoring can be expected such as dehydration level, glucose level and targeted drug and functional food delivery.



Biomedical status monitoring (source Converging Technologies for Improving Human Performance NSF/DOC-sponsored report)

The figure above illustrates the hypothetical use of these biomedical status-monitoring devices when they are combined with wireless communication systems. Individual soldier status can be monitored not only by soldiers working side by side, but also by central units that can be mobile or transmitted to satellite systems. Future sensors may also be embedded bionic chips.

Finally the soldier can also distribute sensor modes (nodes or smart dust) to gather and distribute information via micro IR-sensors, microradar, gas sensors, nanobiosensors which form adhoc networks and function as an ambient intelligence system. He will get info via his PDA, phone, watch and via flexible thin film displays on his uniform or in his visor.

The wireless system will be able to deliver therapeutic and medical treatment and possibly the soldier will in the distant future have cyborg-like functional enhancements (third arm, improved vision like the Aremac system in front of the eye).

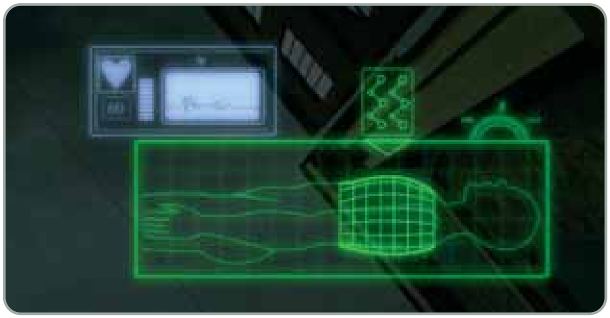

Helmet
■ Lightweight / high impact
■ EEG
■ High impact visor
■ Filtering air
■ 02 supply
Body condition
Micro vehicle
■ Survey / scouting
■ Attack
Teleweapon
linked to
helmet visor
Backpack
■ Lightweight
■ High comfort
■ Lab on chip 1st diagnosis
■ Bio/ food analysis
■ Basic wound treatment
■ Medicine
■ Nutrician
Textiles
■ Climate control
■ All impact protection
■ BC / EMC / bullets
■ Liquid armour
■ Adaptive camouflage
■ Electronic textiles
Micro fuel cell
Shoes
■ RFID tag
■ Custom fit and breathing
Smart uniform

The future soldier will have an all-impact suit enabled by nanomaterials combined with micro or macro fibers, offering protection against bullets, fragment of grenades, bioagents, chemical agents and the influences in combination with the physical status of the body (insulation, ventilation, local cooling). The suit will have integrated BC sensors on label or credit card size for the first generation (4-6 years) and integrated nanofiber networks with absorbing, deactivation and decontamination capacity in the second generation (6-10 years). In the figure on the opposite page one can see again the distinction between technologies which are more nearby (black text) and the technologies which will become available further ahead in the future (greyblue text).
The backpack of the soldier will be lightweight made from carbon fiber or polymer nanocomposite frame covered with a water-tight fabric. In the backpack the soldier will have a basic wound treatment and therapeutics for BC exposure, a medicine and nutrition kit, a portable lab-on chip sampling and sensor system to test his own condition, water, environmental materials and a MUAV (Micro Unmanned Aerial Vehicle) to gather additional intelligence apart from the wireless sensor network on the ground.

His teleweapon is connected to his PDA and visor and also to his commander from a distance so that ultimate precision and lethality can be achieved. His smart helmet is lightweight and has superior anti-ballistic properties due to the use of nanoparticles (bucky CNT-paper, nanofibers) combined with high-strength fibers in polymer composite. The helmet contains also a contactless EEG sensor, an air-filtering system with gas and particle sensor and is of course part of the Body Area Network.

His shoes contain RFID-tags incorporated for access control, positioning, custom-fit application and a BC sensing device to gather and analyze BC agents from the ground.

If electroactive polymers and molecular motors become stable and robust enough the suit will be also equipped with an exoskeleton muscle function for body support and re-animation in emergencies. This could also be used for ventilation and insulation. He will also have an energy conversion - battery/ fuel cell/solar cell system and a preparation and preservation system for food and water.



Exoskeleton muscle reanimation function in suit (source MIT/ISN)

Landvehicle

The future tank or land vehicle should be lighter and will have to fit in larger quantities in the available C-130 like transport planes of the NATO countries. Secondly the tank should be faster and more lethal.
The basic question is whether the future tank should have a traditional large caliber gun in a turret or will be equipped with micro cruise missiles. This will determine the weight together with the armour materials being used.
The aim should be to develop lightweight nano-armour skirt or composite plates to cover the vital part of the tank or land vehicle. This armour could also consist of magneto-rheofluidic systems. The outer layers of the vehicle should have a coating with B/C absorbing and deactivation capacity and will ideally in the long term also have a switchable nanodot polymer camouflage display. Another use of nanomaterials can be found in the bearings, the sealants, and the ammo.
Vital microsystems in the future tank will be the microradar, a large POLYLED command display in the turret and various machine condition sensors for the components which need maintenance (engine, wheels, tracks). Of course the tank will have to have the latest stealth shape and nanocoatings combined with materials which limit the IR-visibility.

With the increase of computing power of nano-electronics unmanned land vehicles (microrobots) with sensors and weapons can be anticipated for surveillance in hostile urban environment, reconnaissance missions and logistics supply.

Source Andrews (ISN)

Vibration / motion correction

Rigid / flexible / nanoplastic comfort

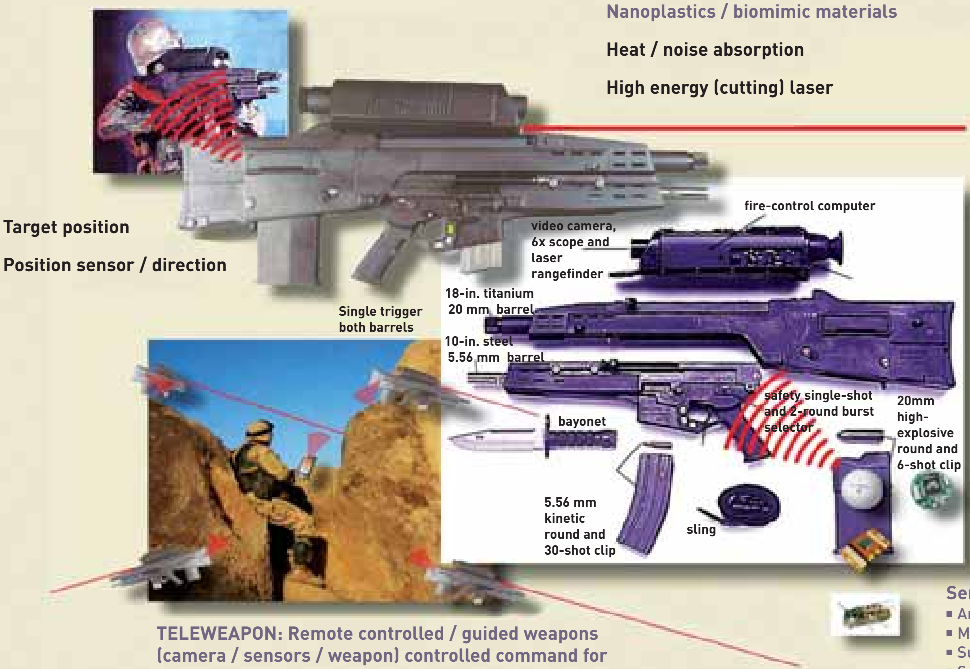
Acoustic pulse jet

Corrective guidance structure

Nanoplastics / biomimic materials

Heat / noise absorption

High energy (cutting) laser



Sensor nodes
- Ammo sensor
- Micro / nano bomb
- Super penetration
- Smart dust
- Non lethal bio-active bombs

TELEWEAPON: Remote controlled / guided weapons (camera / sensors / weapon) controlled command for urban / citycombat (roofs / alleys etc.)
Non mechanical trigger / picture frames / micro radar

Teleweapon

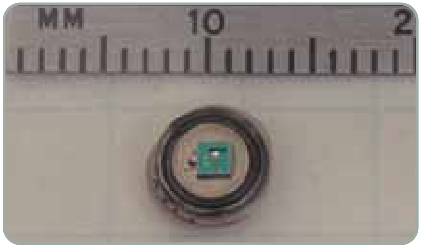
The impact of nanotechnology on weapons seems limited in the short term to 0-5 years. In the long term, 5-15 years, we can expect that nanomaterials can be used in polymer compound to create lightweight structures for guns, rifles and automatic firing systems. It would be very interesting if nanomaterials could create a corrective guidance structure to correct the movement and trembling of the body of the soldier. Ideally this would be a smart adaptive material in the shaft of the gun or on the grip. Other technologies which can be integrated in future weapons for the soldier are: RFID-tags in gun, cartridge, target positioning/recognition (via micro IR camera on gun or PDA, microradar, RF-array, through-the-wall THz radar), wireless link to PDA and smart helmet to pull trigger from a distance (teleweapon), various ammotypes (shaped ceramic materials, softer bullets, high penetration bullets, sensor modes/ smart dust, insensitive tailored explosives to limit collateral damage). The gun will be equipped with a non-mechanical trigger which can be wireless linked to PDA, phone or smart helmet of the soldier. An example of the use of current wireless technology to detonate explosives is the use of GSM-technology by terrorists in Iraq. A high-power laser for hand guns is still far away but not unthinkable.

Nanotechnology could lead to non-lethal bio-active ammo which limits the physical capacities of the enemy for some time to enable one's own troops to advance further in dangerous situations / environment.

The current ultra-low power smart dust modes are relatively large and therefore less useful to be fired or spread with a handgun. It is expected that the size will shrink drastically over the next 10-12 years resulting in 3D nano-electronics system in one chip (radio, battery/power, dsp, sensor, memory).

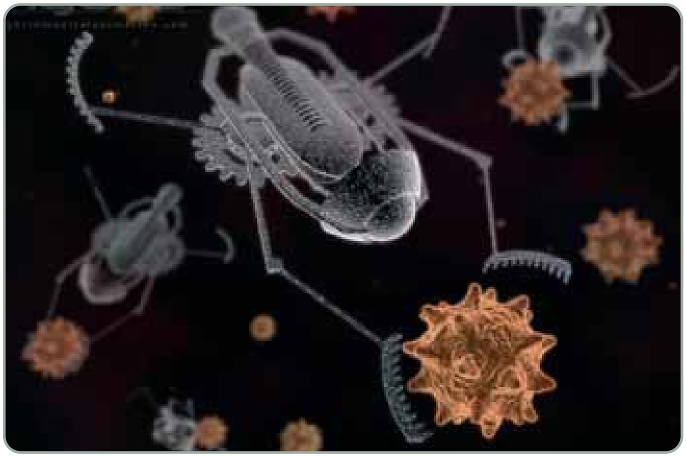
Nanobot and biobots as weapon systems are perhaps to be expected in the longer term (20-30 years).

Smart dust mode of Dust-Inc

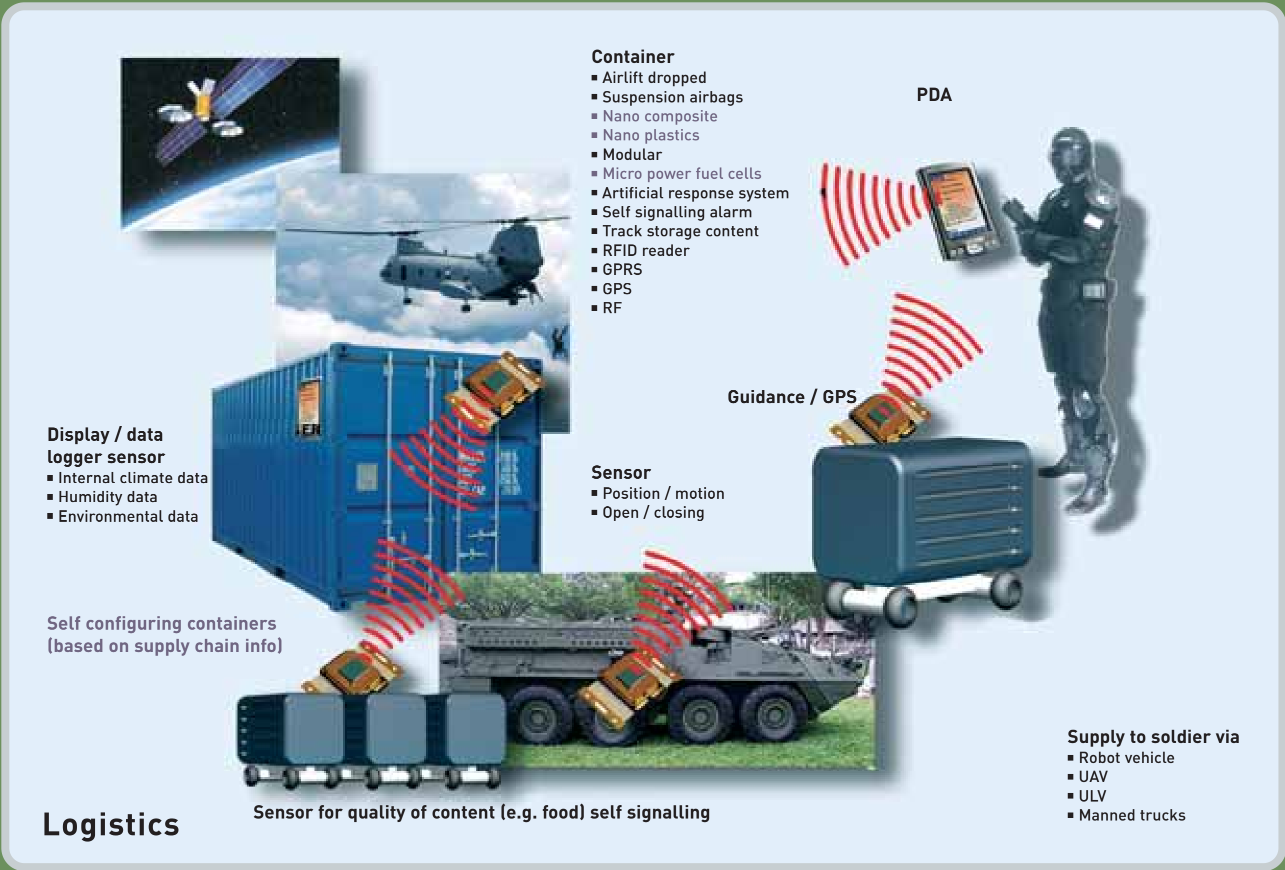


Smart dust mode (UC Berkeley)

Future of smart dust (photo Peter Menzel)



Future nanobots for biological interference (Foresight)

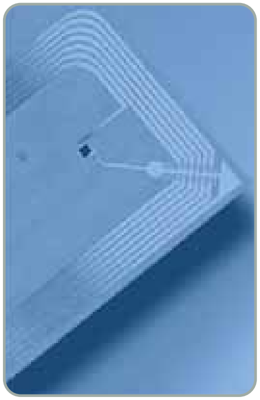

Container
▪ Airlift dropped
▪ Suspension airbags
▪ Nano composite
▪ Nano plastics
▪ Modular
▪ Micro power fuel cells
▪ Artificial response system
▪ Self signalling alarm
▪ Track storage content
▪ RFID reader
▪ GPRS
▪ GPS
▪ RF
PDA
Guidance / GPS
Display / data logger sensor
▪ Internal climate data
▪ Humidity data
▪ Environmental data
Sensor
▪ Position / motion
▪ Open / closing
Self configuring containers (based on supply chain info)
Supply to soldier via
▪ Robot vehicle
▪ UAV
▪ ULV
▪ Manned trucks
Logistics
Sensor for quality of content (e.g. food) self signalling

An essential element of future warfare is logistics. Supply chain management should be linked to the operations in the field to ensure that food, water, ammo and fuel supply are in the right place on time in the desired quantities. Key elements in future logistics are modular containers in various sizes which can be airlifted and dropped at the desired location on land. This container should be lightweight so the use of nanoplastics and nanocomposites could become interesting if the cost level outweighs the fuel consumption of lifting and transporting current steel sea containers. The container will be equipped with micro-sensor systems such as low power DGPS/GPRS modules (for positioning/communication), UHF RFID-readers to check whether certain goods have been taken out of the container, condition sensors (temperature, humidity, B/C), micro fuel cells powering the microsystems, a self-signaling system for events (unloading, movement, high accelerations etc.) and a guidance and positioning system for urban areas (DGPS, UWB, UHF active RF-tags).

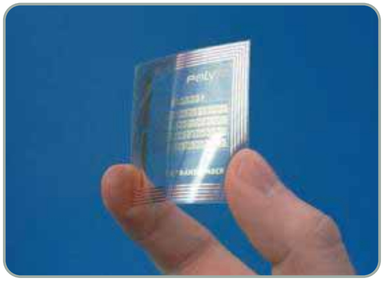
The soldier will order the supplies he needs at group level via his wireless system to the logistics command which will respond and deliver the desired quantity in small or bigger modular containers via traditional transport (humvees, land-rovers, trucks) and in the future partly by robotic land and air vehicles.

In the distant future (15-25 years) self-configuring containers can be anticipated which gather goods and distribute these almost automatically via the supply chain to the end-user.

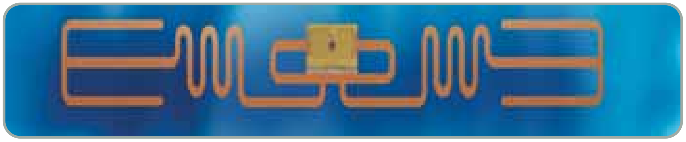
In the course of next year one can expect an increasing use of RFID-tags for tagging food packaging on cardboard box level, pallet level and container level. These RFID-tags will probably be UHF EPC tags with dedicated antennas on tags and in the stationary and handheld RFID readers to ensure 100% detection of goods and limit the influence of water and metal. There's a need for low-cost sensor tags for monitoring food quality (temperature, humidity, microbiological deterioration). This sensor function can be created by using structurized con-ductive polymers in a RF-circuit.



13.56 MHz RFID-tag with Cu-antenna and silicon chip



Polymer 13.56 MHz RFID tag of PolyIC



UHF label Alien Technologies

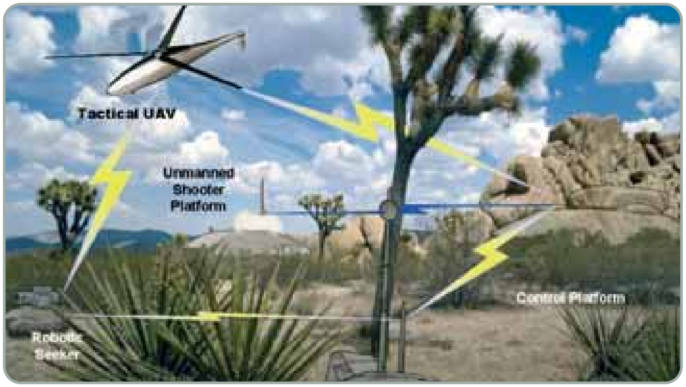

Organic robot structures
Bio-robots
UUV / UAV
Vehicles
▪ Air / ground / nautic
▪ Survey / scouting
▪ Attack
Micro vehicles / robots
Remote control guided

Micro vehicles and robotic systems will become more dominant and versatile in the future, due to the increasing computing power and memory capacity of nano-electronics, the reduced weight of the mechanical structures (use of nanocomposites, adaptive structures for movement) and the increasing endurance of portable power. The ultimate goal will be to create nanorobots or nanobots for activities on land and NUAV (Nano unmanned aerial vehicles) for reconnaissance and sensoric activities in the air (flying artificial insects). Also uninhabited combat vehicles (fighter, submarine, vehicle) with a higher performance and a lower casualty risk can be expected. A crucial factor is the weight of the portable power: until now most flying insects or MUAVs don't endure sufficiently in the air due to limitation of the power (mostly battery) source. Some research projects focus on the use of biological mechanical movement such as that provided by insects, birds or other animals, which should be controlled by micro or nano brain interfaces giving the right stimuli. Ideally all micro vehicles and robots should be less visible for enemy troops (biomimic structures), should last long enough to gather essential information and should be low cost and therefore redundant.

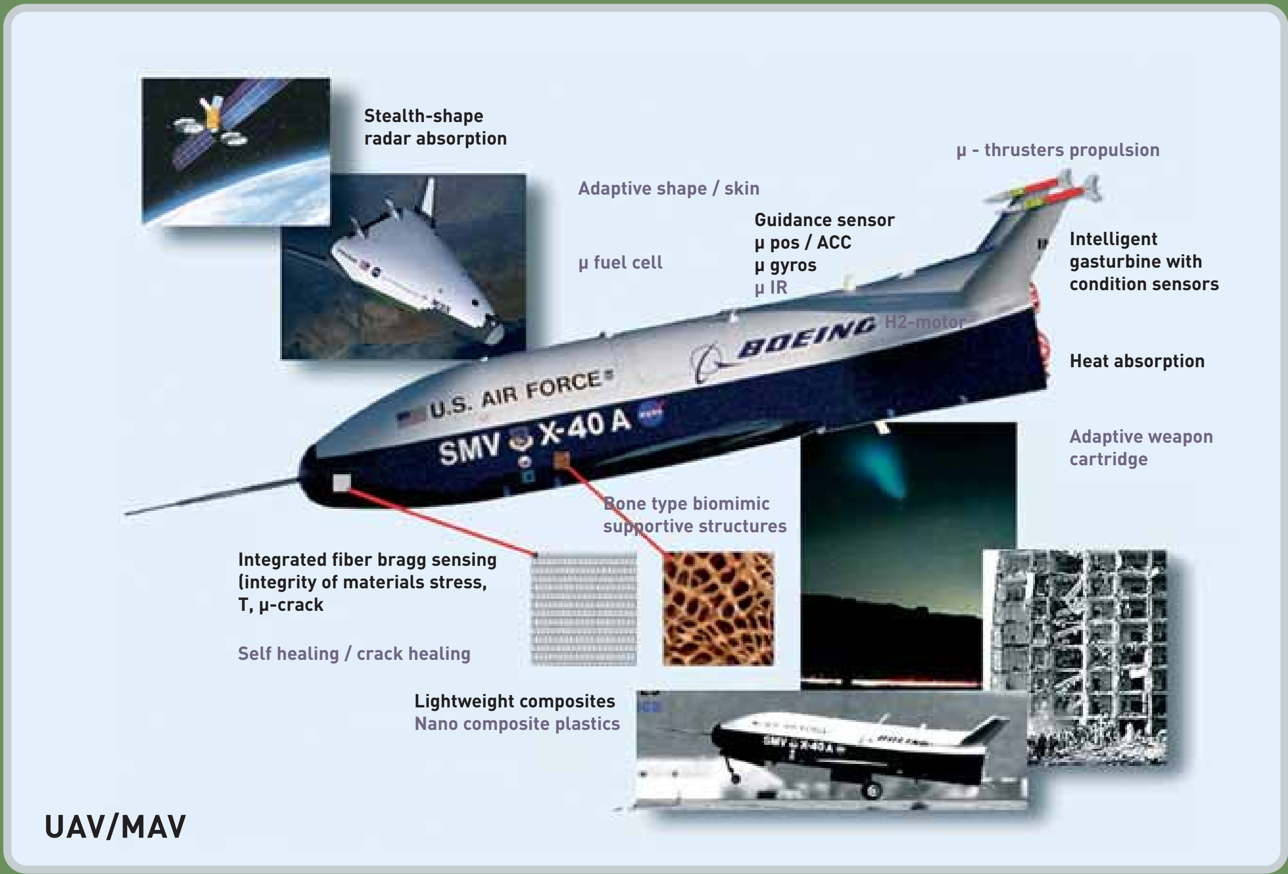
The ornithopter of Caltech/UCLA had the following characteristics: a mass of 11 grams, a flight endurance of 6 min 22 seconds, a wingspan of 6 inches, a battery power of 1.5 Watt. The final conclusion of the project was that for the time being it would be cheaper to use a biocontrolled pigeon and equip it with a camera or other sensor.

A crucial factor for the use of these robotic systems is a network-centric approach in which the individual warfighter can analyze, interpret and decide on the information and can control the robots through visual radio and audio aids. Effective training is needed through virtual reality systems.

Caltechs/UCLA's battery powered MUV ornithopter for DARPA



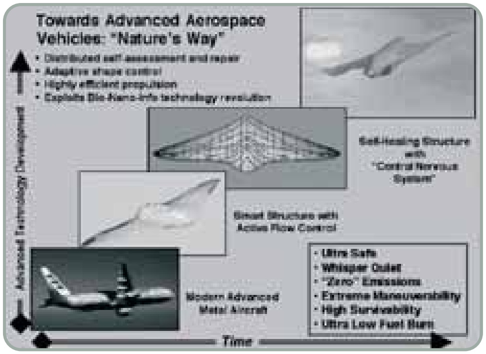
Network centric approach for robotics

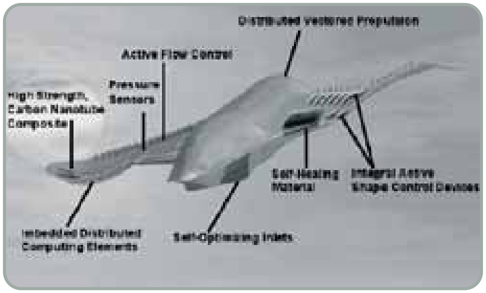

Stealth-shape
radar absorption
Adaptive shape / skin
μ - thrusters propulsion
Guidance sensor
μ pos / ACC
μ gyros
μ IR
μ fuel cell
Intelligent
gasturbine with
condition sensors
H2-motor
Heat absorption
Adaptive weapon
cartridge
Bone type biomimic
supportive structures
Integrated fiber bragg sensing
(integrity of materials stress,
T, μ-crack
Self healing / crack healing
Lightweight composites
Nano composite plastics
UAV/MAV

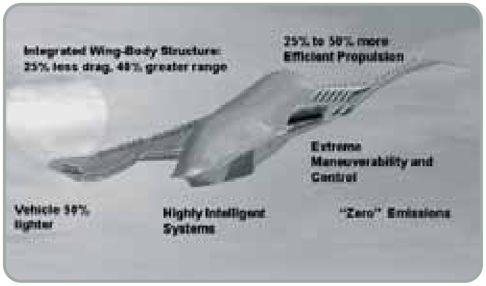
Unmanned aerial vehicles or manned aerial vehicles with larger dimensions seem to have more realistic potential for the operations in the next 5 years. A number of robotic aeroplanes have already been developed in the past for reconnaissance tasks. Aerial vehicles can be equipped with microthrusters for precise movements, with intelligent gasturbines with sensors, air-inlet and flow control, with guidance, acceleration and gyros sensors, with integrated fiber bragg optical sensors in the skin, with structures for stress and crack sensing and with stealth shape and radar-absorbing materials. For the period of 10-20 years from now vortex control with MEMS structures, biomimic bone-type structures, smart adaptive and self-healing skins can be expected.

The use of reinforced plastic such as carbonfiber composites will be followed by the introduction of nanocomposites with carbon nanotubes and or nanofibers as reinforcing fillers in composite plastics. Essential factors will be the use of high strength-to-weight materials, fire-resistant composites, smart materials which can sense and actuate, multispectral index of refraction change, energy-efficient fuels and propellants, active camouflage and protective coatings.

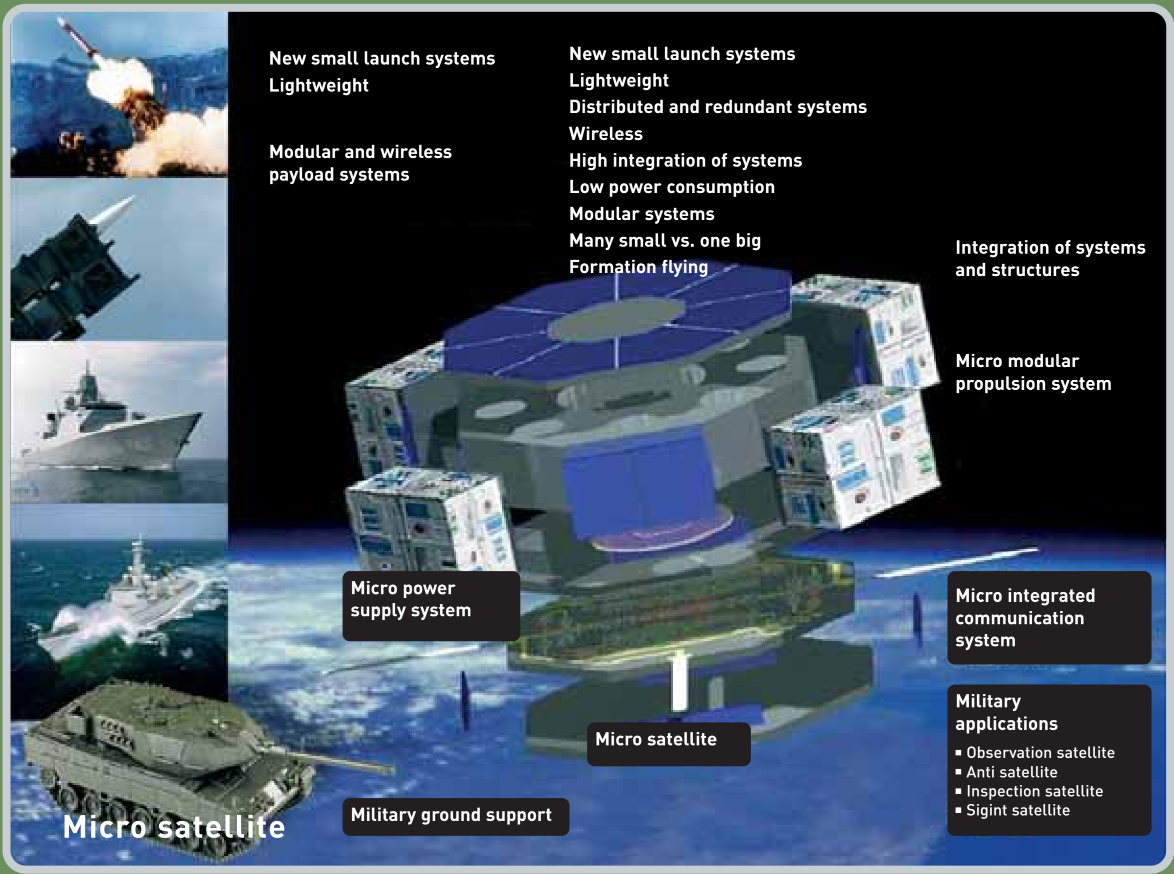
Future airplanes (photos by NASA, Boeing and Lockheed)







NASA's vision of a future flight vehicle


New small launch systems
Lightweight
Modular and wireless
payload systems
New small launch systems
Lightweight
Distributed and redundant systems
Wireless
High integration of systems
Low power consumption
Modular systems
Many small vs. one big
Formation flying
Integration of systems
and structures
Micro modular
propulsion system
Micro power
supply system
Micro integrated
communication
system
Military
applications
▪ Observation satellite
▪ Anti satellite
▪ Inspection satellite
▪ Sigint satellite
Micro satellite
Military ground support
Micro satellite

Major advances in the microsystem technology, in particular microprocessors and microsystems, have made smaller satellites a feasible alternative for large satellites. The use of micromachined devices can revolutionize the way in which satellites are designed and built. Besides reducing their size, weight and power consumption, the use of micromachined devices would give far better component integration in areas such as propulsion, communication, data processing, power generation and navigation. Micro or small satellites will therefore have a significant lower weight and size than existing present satellites. This will make them cheaper to manufacture and to lift into space orbit. Ideally one could launch into orbit a number of redundant micro satellites which can be wirelessly connected to each other. Each microsatellite has its own power source/solar panels, dedicated sensor system, micro modular propulsion / thruster system, and navigation sensors. The microsatellites can be launched in batches in a modular container system. This is already in use for ESA missions. The average size of a microsatellite is approximately 1 dm^3. Possibly the sizes will shrink more in the future due to increasing computing power of nano-electronic systems and lower power consumption. Essential for all small and micro satellites is the durability, the protection against radiation and other particles and the position in orbit. It can be expected, that the trend towards smaller satellites will continue in the coming years. The state of developments in the micro and nanotechnology is an important factor for decreasing the mass of satellites. However, if the technology reaches its ultimate technology boundaries, the size of satellites will reach their minimal size and weight.

For military use the swarms of microsatellites can fulfill functions such as observation, inspection, anti-satellite communication etc. and will be connected to the information gathering and control system. Advantages of small highly integrated modular satellites for military purposes are that they can be used as destruction satellites, spy satellites and they can be part of a swarm of satellites, launched at the same time. Destruction (anti satellite) and spy satellites can fasten on large satellites without being observed and can destroy important parts of the satellite or they can intercept the communication or observations. Swarm formation flying can give high resolution observations.

This platform shows that military small satellites can be used for the detailed observation of the enemy (e.g. where is the enemy, how many people, human search, house observation of potential terrorist), which can be communicated to each military partner. Thereby, small satellites can be used as space systems.

Group name	Satellite mass range (kg)
Minisatellite	50-500
Microsatellite	10-15
Nanosatellite	1-10
Picosatellite	< 1

How can nanoscience enable the future warrior?

Future warrior concept US Army

08. Concept developments for Dutch defence organization

For the current and foreseeable future tasks of the Dutch defence organization, the role of the soldier is becoming more and more important and versatile. Peace-keeping tasks require operations in an urban environment with specific tasks towards the population, together with a high level of situational awareness for hostile attack. Operation in small groups, with specific tasks, self-supporting and highly maneuverable is often needed. Therefore the first focus for future technologies is on the soldier.

Nanomaterials for the soldier: uniform, helmet, equipment

Nanotechnology for the soldier is directly related to new functionalities in his suit, helmet or other portable equipment. Technologies with potential use for the soldier are:

- integrated sensors (RFID+) and actuator arrays: body, health & environmental monitoring
- directed RF tracking-tracing-identification
- anti-ballistic protection (flexible, lightweight)
- BC-sensing and protection
- adaptive: switchable insulation, camouflage

Six concepts

Six concepts have been defined for further discussion and elaboration:

- smart helmet
- antiballistic material for helmet
- smart suit, BC sensing and health monitoring
- flexible antiballistic material for the suit
- health monitoring and wound treatment
- adaptive insulation and ventilation in suit

The underlying basis for this initial choice is the fact that key elements of the future (Dutch) soldier will be his equipment and in particular his helmet, his uniform and the intelligent systems he is wearing on or in his uniform and helmet.

These intelligent systems should inform him whether there are nuclear, biochemical or radiation threats, should tell the soldier and his commander/medic/fellow soldier about his physical and eventually also about his mental condition and should give the right insulation when needed and ventilation.

Traditionally the Dutch industry has a strong position in fiber development and application for all kinds of fabrics and composite structures. This implies that it seems logical to focus on nano and micro research and development projects which include the use of existing fibers which will be adapted or differently incorporated in end-materials for the uniform and helmet.

Antenne Sensor Array (ASA) on helmet

The smart helmet consists of a helmet as platform system equipped with an intelligent sensor system for various tasks: positioning, RF and audio communication, B/C sensing, EEG monitoring, sniper detection and digital signal processing. The helmet is a form-stable object, so therefore a good base for sensor arrays. In general, it is even the only firm base, the garment is usually flexible. The second advantage of the smart helmet is its position, it is usually the highest point of the soldier. Suitable sensors for the helmet are:

- optical/IR camera (360° vision)
- RF array antennas for positioning, friend or foe RFID and directed low power and efficient communication
- acoustic arrays (microphones)
- B/C sensor arrays as early warning system
- wireless EEG sensor.

Optical/IR camera array

- 360 degree coverage (6 camera's)
- useful for detection of laser designators, night vision, surveillance.
- cameras are available in small size, in the near future the electronics for complex 360 degree signal processing will fit in the helmet .
- applications requiring simple signal processing, like laser detection, can already be integrated in the helmet.

Array antennas

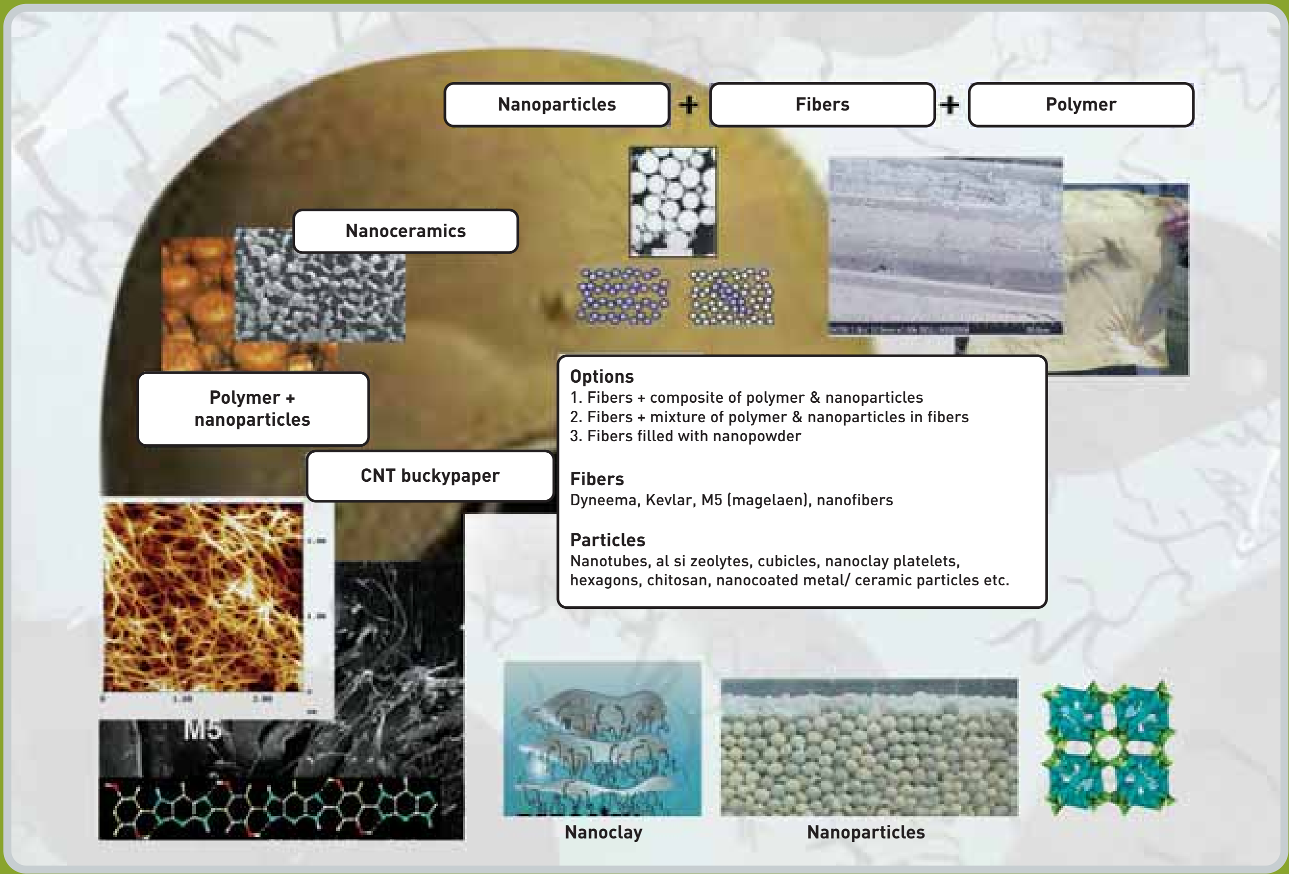
The helmet can take advantage of conformal array technology. Using conformal array technology, antennas no longer need to be "flat" but can follow the curvature of the helmet. For popular frequencies on the battlefield, for example 60 GHz, conformal arrays can be of great added value in beam forming. Communication beams can be directed to the conversation partner of interest. Used as radar antenna, they eliminate the need for a mechanically steered antenna.

The beam of an antenna array can be electronically controlled, creating a beam that can jump instantaneously from radar target to radar target. The proposed antenna array on the helmet could consist of a single 60 GHz array ring around the helmet for terrestrial communication and radar, and a 10-15 GHz array on top for satellite communication. The satellite array should be combined with the GPS antenna. The RF and microwave electronics, as well as the beam-steering electronics, can be integrated with the helmet. Switchable antenna arrays will be less visible for the enemy and can be possibly created with conductive materials.

Acoustic array

For acoustic arrays similar principles apply as for antenna arrays. For frequencies higher than 1000 Hz, acoustic array technology can be applied. Electronics can be hearing-aid sized. There are two applications: beam forming, a "listening beam" and direction finding, the direction from which a gunshot is detected can be determined. Acoustic detection is greatly improved when soldiers share each other’s acoustic detection information, which requires mutual communication links.

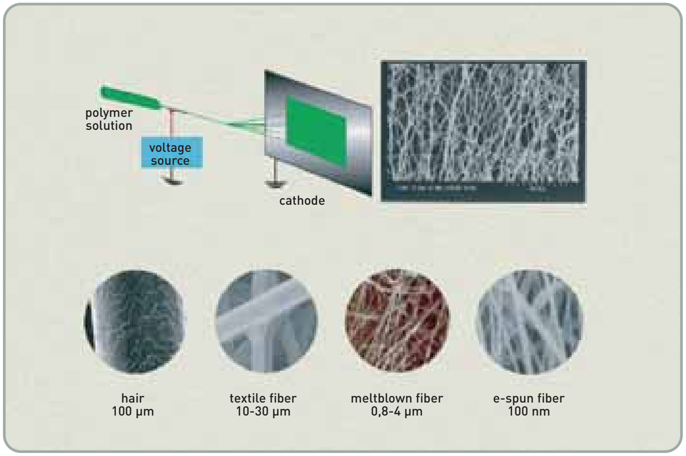
Anti-ballistic materials for helmet



Closely connected to the concept for the smart helmet is the concept for anti-ballistic protection via a lightweight helmet consisting of a combination of polymers, fibers and nano-materials. This new nanocomposite should have a higher impact resistance than present fiber composite systems and should have a significantly reduced weight. Most promising seems to be the application of nanofibers and buckypaper in combination with present high-strength fibers and polymer material to create new composite material.

For the next generation of helmets the use of present fibers such as Kevlar, Dyneema or M5 is most realistic in combination with nanomaterials which can enlarge the strength of the composite and which can keep the fibers closely packed in the composite structure at impact. M5 is the newest type of fiber in this category and product applications of this fiber are expected in the next few years. Nanoclay in a sillіputty type of polymer matrix combined with fibers is a possible alternative. These high-strength fibers can, in theory, bring significant improvement. The same applies to metal nanoparticles coated with a multiple-layered ceramic nanocoating. These coatings have originally been developed for turbine blade protection but the extreme hardness is also of use for anti-ballistic nano fillers in composites.

In the long term (10-15 years) a more dominant use of electrospun nanofibers to create the basic fiber strength in the composite can be expected. These CNT fibers and other nanofibers have a theoretical strength of 130-180 GPa.



Process for electrospinning of nanofibers and comparison in size with other fibers

Anti-ballistic materials for suit

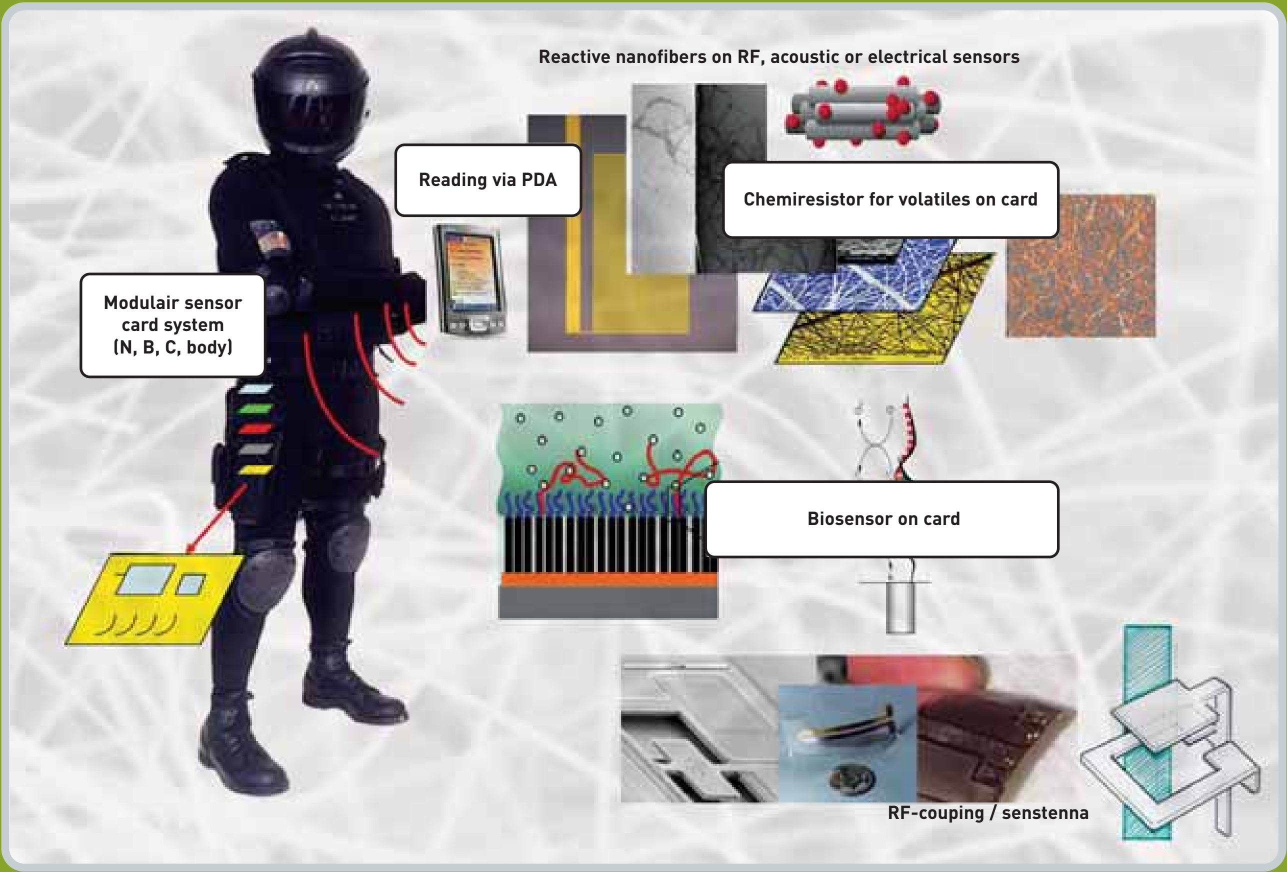
Thanks to the technological advances in high-strength polymer fibers such as carbon, aramide and Dyneema, the performance of anti-ballistic suits has been improved considerably over the last 20 years, with subsequent reduction in weight (30%). These suits with integrated or inserted composite fiber structures are quite effective and are being successfully applied for ballistic protection of the body. The composite structures, however, are not sufficiently flexible to be used for protection of the body extremities such as arms, legs and neck. At present, injuries of these extremities have become the dominant factor in casualties, especially from bombings and subsequent shatter, resulting in loss of military power and high costs of medical treatment. In view of this, several concepts for flexible armour have been proposed and are now in development such as:

- magneto-restrictive fluid: a nanoparticle filled flexible medium that can be electrically activated to become rigid (active system, MIT-ISN)
- shear-thickening fluid: a nanoparticle-filled binder for high-strength textile that is flexible under low shear rate and that becomes rigid under high shear rate impact (passive system, ARL). This nanoparticle-filled system inhibits deformation and sliding of the high-strength fibers in the fabric at high shear rate.
- silliputty-type of elastomers in combination with ceramic armour: elastomer system which is deformable and elastic at low shear rate and stiff at high shear rate. Similar to shear thickening fluids, but up until now less effective in anti-ballistics (passive system, e.g. D3O material).

The shear-thickening fluid system seems quite promising: it is passive, there's no need for electrical powering and it has already a reasonable performance. It needs, however, further development and optimization.

To develop this concept further, a technology development program has been defined aiming at flexible lightweight armour for ballistic protection of body extremities. The program will cover development and optimization of a nanocomposite binder in combination with a high-strength fiber fabric and will demonstrate this technology in prototyped armour suits. Ideally the future combat suit gives a basic protection against debris, shatter and smaller caliber bullets and gives the combat soldier a high degree of freedom.
This can be realized by using present fiber systems such as the Dyneema fiber and combining this with a filler, or impregnating with filled liquid or another binder consisting of a polymer material filled with nanoparticles (platelets, cubicles, zeolytes, carbon nanotubes, nanofibers etc.). Key function of the nano-polymer material in, around or in between the microfibers is to keep the fibers together at bullet hits and to limit tissue damaging. The aim is to create a flexible body armour system which is basically a lightweight augmented Kevlar system and comes closer in performance to ceramic plating.

BC sensing and health monitoring in suit

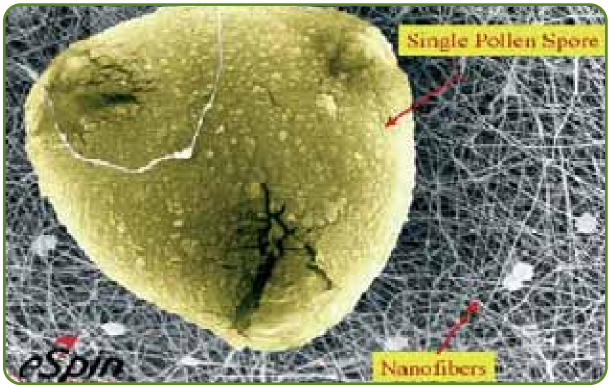


For soldiers in the field it is essential to get an early warning when they are under a bio, chemical, nuclear or radiation threat. For immediate detection and response, a mobile and preferably wearable system is needed. Chemical species to be detected are:

- VX
- soman
- musterdgas
- lewisite

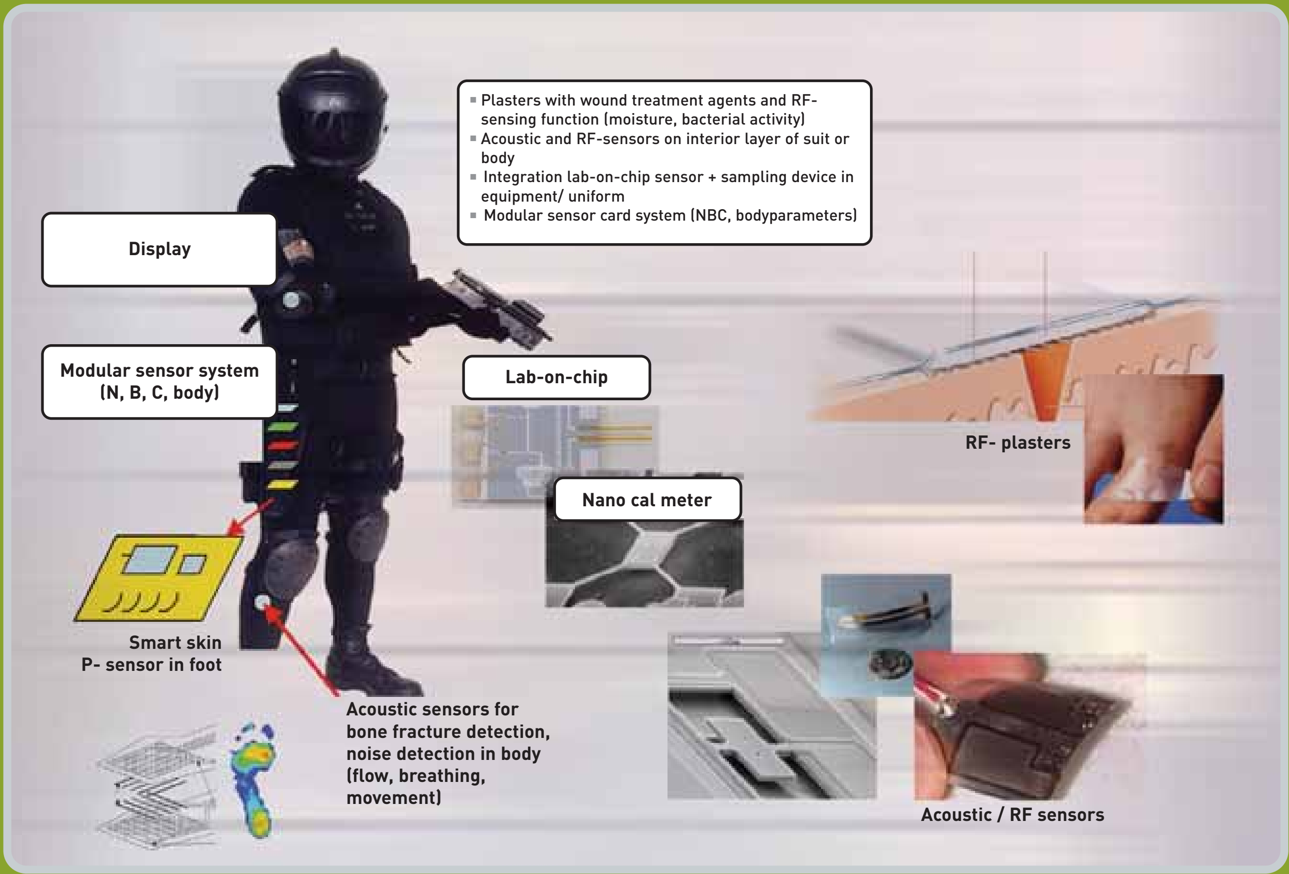
Ideally these sensors should be integrated in the suit as woven or non-woven structures of functionalized nanofibers which sense, absorb and deactivate bio and chemical agents and block off the ventilation of the suit when needed by creating an adaptive BC protection suit. This concept is to be expected in 10-15 years from now. The next generation of B/C sensing system is supposed to be put on credit-card-sized semi-active or passive sensor tags with reactive large area surfaces (electrodes with carbon nanotubes, nanofibers on sensor surfaces, reactive dielectric materials in capacitor rf-sensors etc.). The idea is to read and scan these sensors wirelessly with the soldiers PDA or watch.

Several configurations of sensor cards can be put in the suit that can also monitor body condition. These sensor tags can also have the shape of labels or credit cards and can via direct contact with the body or via near-field communication check hydration levels, body temperature, glucose/lactate levels, ECG patterns. A combination of a silicon RFID-chip, a biosensor and a rf-antenna is one of the possible configurations for this purpose. The senstenna concept can also be integrated in these type of systems. When needed local DSP can be integrated to provide only interpreted data to the soldier's user interface on PDA, watch, smart helmet etc. The use of early biomarkers via the system biology approach to gather relevant information about the body at an early stage is also an interesting theme in prognostic or diagnostic early analysis.



Single pollen spore on nanofibers (photo eSpin)

Health monitoring and wound treatment



Health monitoring and wound treatment

For medics it is essential to know which soldier needs immediate care and which soldier is not directly in danger. A modular sensor tag card system can gather data, e.g. combined with acoustic info regarding sniper hits and transmit these data via the BAN system and PDA to the medic and commander. Immediate action can be undertaken and operations can be adapted to the new situation. Acoustic sensors (ultrasound sensors) can detect bullet hits, bone fraction and can detect noises in the body of breathing, movement etc. RF-sensors can give data regarding temperature, moisture levels, bacterial contamination. For monitoring of the health condition the following functions are needed:

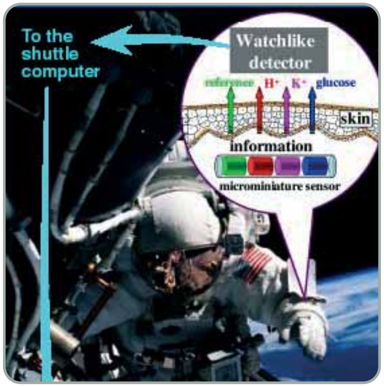
- heartrate and heartrate variability (ECG, stress monitoring)
- internal body temperature
- respiration rate
- blood pressure

Wounds can be dressed with intelligent band aids which monitor the moisture level, the bacterial activity and which release anti-microbials on nanoparticles to kill bacteria.

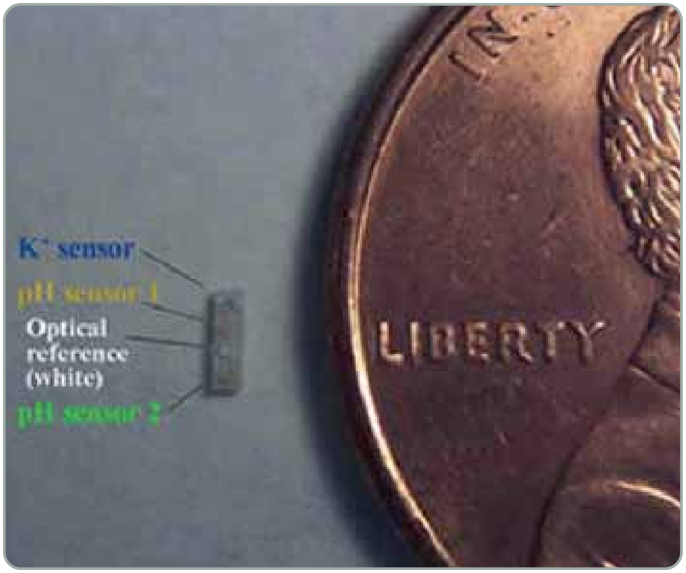
Part of this health monitoring system can be a portable sample preparation and lab-on-chip analysis kit enabling the soldier to test his own body fluids when he needs more specific data and water and food. Ideally this analysis system will be built into his smart suit and will be able to detect bioagents and to apply anti-dotes to the soldier (vision of MIT/ISN). This seems still far away.

Biosensor for body-function monitoring can be expected to be integrated subcutaneously in the body of future combat soldiers. NASA is already working on implanted (sub skin) passive silicon sensors which can be read wirelessly from outside the body. Core temperature measurement with a swallowable passive RF-sensor is one of the solutions for accurate and low cost core temperature measurement of soldiers in combat.

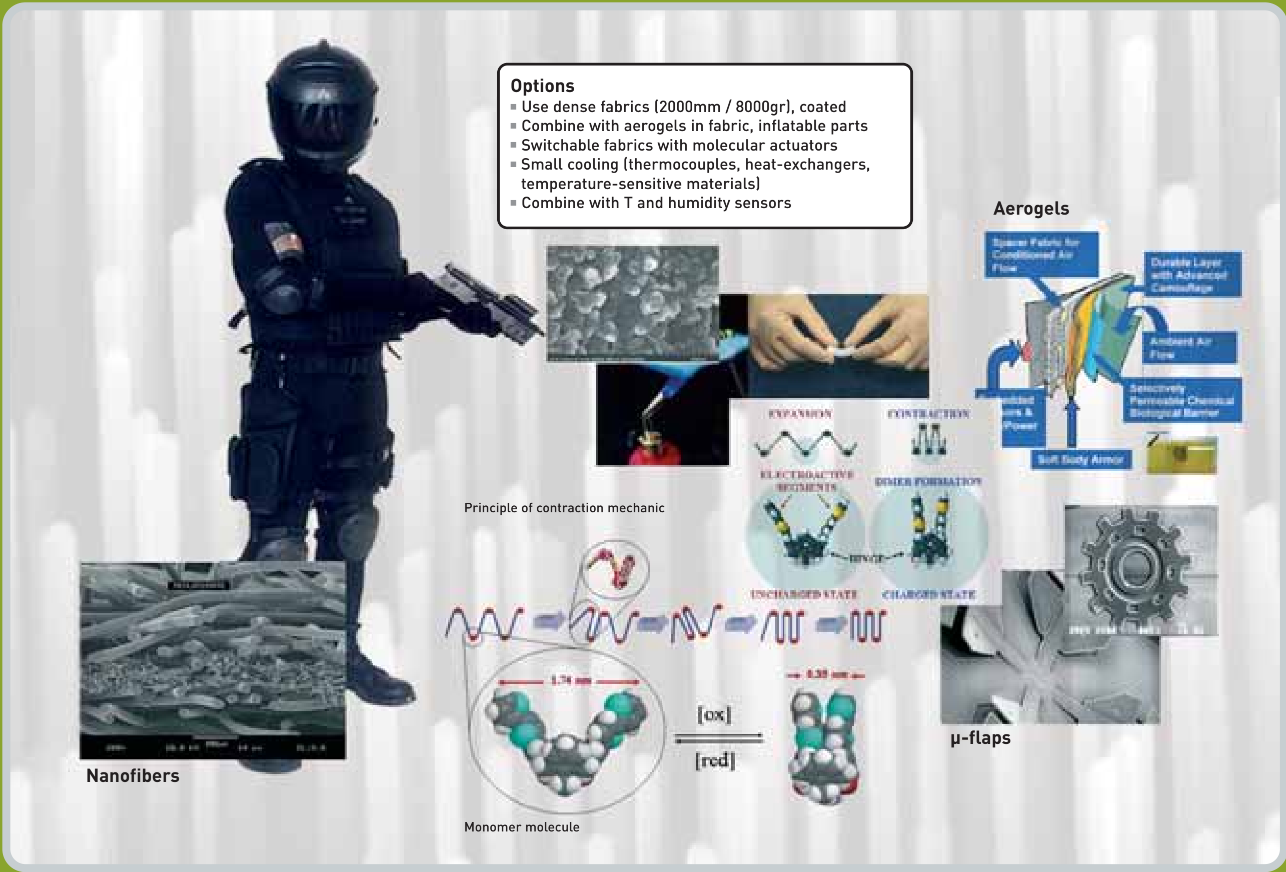
Inkjet-printed bio-glucose sensors based on an enzymatic activated glucose oxidation measurement cell that can be read electronically are also in a development stage (Case Western Res. Univ, Cleveland).



Body sensor for astronauts (Glennan Microsystems, NASA Glenn)



Ventilation / insulation

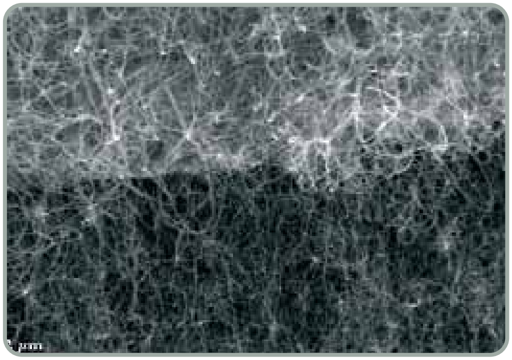


This concept consists of a switchable insulation and ventilation fabric for use in future combat uniforms. The soldier will generate heat during exercise and practice, and to maintain his optimal performance level he has to reduce his body temperature by adjusting the ventilation systems of the suit. This can be done with electroactive polymers which can be contracted or elongated at low voltages. MIT and UCLA are already working on these polymers. Key research question is to make them stable and contractive at low voltages. Ventilation can also be provided by using nanofiber fabrics which let pass water vapour and air but block water and other liquid or vapor-type materials.

Possibly extra ventilation can be provided by micro flaps and rotors integrated in the fabrics. For insulation the use of densely woven fabrics will lead to wind-proof insulating fabrics. These can possibly be combined with cross-linked aerogels, carbon nanotubes which have a high heat dissipation.

X-aerogels have potential for use as high-insulation materials, require simplified processing, have an improved machinability, are flexible and have a higher strength than aerogels. This material will probably be developed further for astronaut suits and other space applications first, but has potential as filler in future fabrics for a combat suit.

Carbon nanotubes can easily dissipate excess heat and are therefore an interesting option to be researched further as filler or additive in fabric structures for cooling purposes. Also CNT composites and nanofibers have potential in this area. They are flexible, have a high strength and a high thermal conductivity. Electrospun nanofibers offer good potential as insulating materials, thanks to low mass, high strength and a high surface / volume ratio.



Nanofibers

Institute for soldier nanotechnologies

Focus and adapt nanotechnology research to significantly enhance Objective Force Warrior survability

Sensors
- Multi-spectral & acoustics

Fightability
- Mechanical/ human enhancement

Stealth
- Reduced signature

Environmental protection
- One piece multi-functional suit
- NBC threat protection
- Physiological & causality care

Medical
- Automated selfmedicating system

Approach
- Creative university Affiliated Research Center focusing critical mass of research on army needs
- Industry partnership / participation
- Accelerate transition of research products

Goals
- Enhance Objective Force Warrior survability
- Leverage breakthroughs in nanoscience & nanomanufacturing

A revolutionary capability for the Objective Force Warrior

09. Civil versus defence driven nanotechnology

Nano- and microsystem technologies are subject of many R&D programs for civil application (materials, life sciences, electronics, sensors) as well as for military uses (weapons, structural material, sensor, protective materials, electronics). Some subjects are covered by both civil-oriented and defence-oriented programs. A number of microsystems have already been introduced in civil applications (tyre-pressure sensor, wireless sensor networks, lab-on-chip systems, accelerometers, condition sensors) which also applies to some nanomaterial application (nanoclay and carbon nanotubes masterbatches for nanocomposites).

Based on the technology radars which visualize all relevant microsystem- and nanotechnologies for the military and civil application areas a classification is proposed for all microsystem- and nanotechnologies into the technology radars. The technologies have been divided into four main categories: Biology, Energy/power, Information and Materials. A further distinction has been made on the questions whether the technology has a principally offensive or defensive character and whether the technology is an improvement of existing technology or a completely new technology. This overview is listed in appendix II.

The following dominating or main technologies impacting on military operations can be identified:

Civil-driven:

- wireless μ-sensors
- RFID
- lab-on-chip
- lw structures & nanocomposites
- body area network
- health monitoring
- wound treatment
- flexible displays
- nanoparticles

Civil- and Defence-driven:

- small and micro power
- water treatment

Defence-driven:

- anti-ballistic materials
- high energetic materials
- bio-chemical sensing and protection
- array sensors (directed, high performance)
- actuators (body support, ventilation)
- camouflage (via CNTs, aerogels, nanodots)

Future now: soldier launches a Raven “Unmanned Aerial Vehicle” (UAV) to conduct reconnaissance for insurgents in Iraq (Photo US DoD)

10. Conclusions

This book is the result of one year of nanotechnology survey and gives a momentary overview of civil and defence-oriented technology developments[1]. The main findings are:

- exploitation of nanotechnology is already part of society, with high investments worldwide
- many nano products already exist on the market (additives in cosmetics, paints, polymers, catalysts, filters)
- some products are expected to come soon (within 5 years), especially wireless tags and nanosensor systems
- others are expected to come later, in a timeframe of 5-15 years (high-strength nanomaterials, smart/adaptive materials)
- more and more nanotechnology is being converged with other technologies, especially biotechnology, information technology and cognitive science
- the defence organization can gain a lot of benefit from these new technologies and should actively participate in these developments

This year the focus has been on the soldier system.

Opportunities for soldier system

Nanotechnology can offer the soldier better equipment that enables a higher security and safety level, better operational capacities and effectiveness. Next to commercial developments such as nanosensors (lab-on-chip, electronic noses etc), tags (RFID, sensortags), wireless communication systems and nanomaterials (nanocomposites, nanomedicine), the following technologies and products are considered to be essential for the future soldier:

- nanocomposites for flexible, wearable antiballistics
- nanofibers for smart textiles (sensoric, BC decontaminating, high strength)
- smart suit (sensor integration, BC protection, switchable fabrics)
- smart helmet (integrated sensor-arrays in lightweight antiballistic helmet)

We expect that these products can become available within a time-frame of 5-10 years, provided that sufficient R&D investments are allocated by the Ministry of Defence and industrial parties with complementary knowledge. Elements of these developments could be fitted in the soldier modernisation program and could be also subjects of international cooperation.

Some NATO countries are executing and/or developing R&D programs which contain elements of the key technologies described above (USA, UK, Germany, France, Sweden, Canada). International collaboration with one or more of these countries might be interesting if they can supply or bring essential technology or know-how.

Next steps

- continuation till the end of 2008 of this nanotechnology study with focus on other platforms such as vehicles, participation in NATO AVT panel 138
- start of a nanotechnology program for the soldier system.
  - definition of nanotechnology program for the soldier based on the above-mentioned topics
  - integration with the ongoing soldier modernization program will be investigated
  - define international R&D co-operations (Canada, Sweden, USA)
  - invite industrial parties to participate in the program.
- extension to other platform systems at later stage.

1) Although the Ministry of Defence and TNO are aware that nanotechnology could introduce ethical concerns and/or environmental, health and safety risks, these concerns and risks are not covered in this study because they are subjects of study by other ministries and organizations (i.e. Rathenau Instituut)

Artificial muscles and electronic textiles for future soldier system
(photos/illustrations: MIT/ISN, US Army Natick Soldier Center)

11. Acknowledgement

The study has been initiated and funded by the NL Defence Material Organisation, who also actively contributed in discussions and workshops. Also many TNO colleagues helped in providing information and advice. Acknowledgement also goes to a long list of R&D centers that were willing to discuss and exchange information on this exciting topic.

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- Institute for Defense Analysis, Clifford Lau, Vashisht Sharma

Near future combat systems vs far future cyborg vision from film industry (photos US Army, Boeing)

Appenidix 1 Nomenclature and abbreviations

ambient intelligence
a system with distributed (wireless) and intercommunicating sensors that can monitor events and persons and can react to and activate facilities in the nearby ambience

ambulant body sensors
wearable sensors for monitoring body functions (heart, brain, hydration etc) and body fluids (blood, urine, respiratory etc.)

acoustic array
1D or 2D array of acoustic/ultrasound transducers (typically MHz region) for high-resolution acoustic sensing and imaging

ARL
Army Research Lab (Aberdeen Proving Grounds, USA)

biometric identification
identification based on bio-characteristic measurement (iris, fingerprint, dna, face)

biomimic materials
materials that look-a-like biomaterials and functions such as wood, bone, shell, structures, optical facets, tissue repair techniques, lotus flower coatings etc.

biorobotics
robots that are partly electromechanical and partly living animal

Carbon NanoTube (CNT)
Cylinder-shaped nanostructure made from carbon atoms resulting in higher strength, better conductivity, higher absorption etc.

EAS
electronic article surveillance (aka electronic anti-theft security)

fiber bragg sensor
structure-integrated optical waveguides with sensing capability (e.g. temp, stress, strain, integrity)

flexible/rigid materials
materials that can switch between a flexible and a rigid state, enabled by nanocomposite technology

GPS
Global Positioning System, determine position of persons and objects (cars, planes, ships, goods etc.) via tri- or quadrangular measurements of distance to global orbit satellites

microbots
robots and engines at micro-dimensions

micro nuclear battery
electricity-generating microsystem powered by nuclear isotopes

micro fuel cell
electricity-generating microsystem powered by hydrogen

nanoassemblers
desktop manufacturing of any type of molecule/drug/material based on nanotechnology

nanobiomunition
biochemical ammunition in a smart switchable package on nanoscale (release under specific conditions)

nanobots
robots and engines on molecular scale

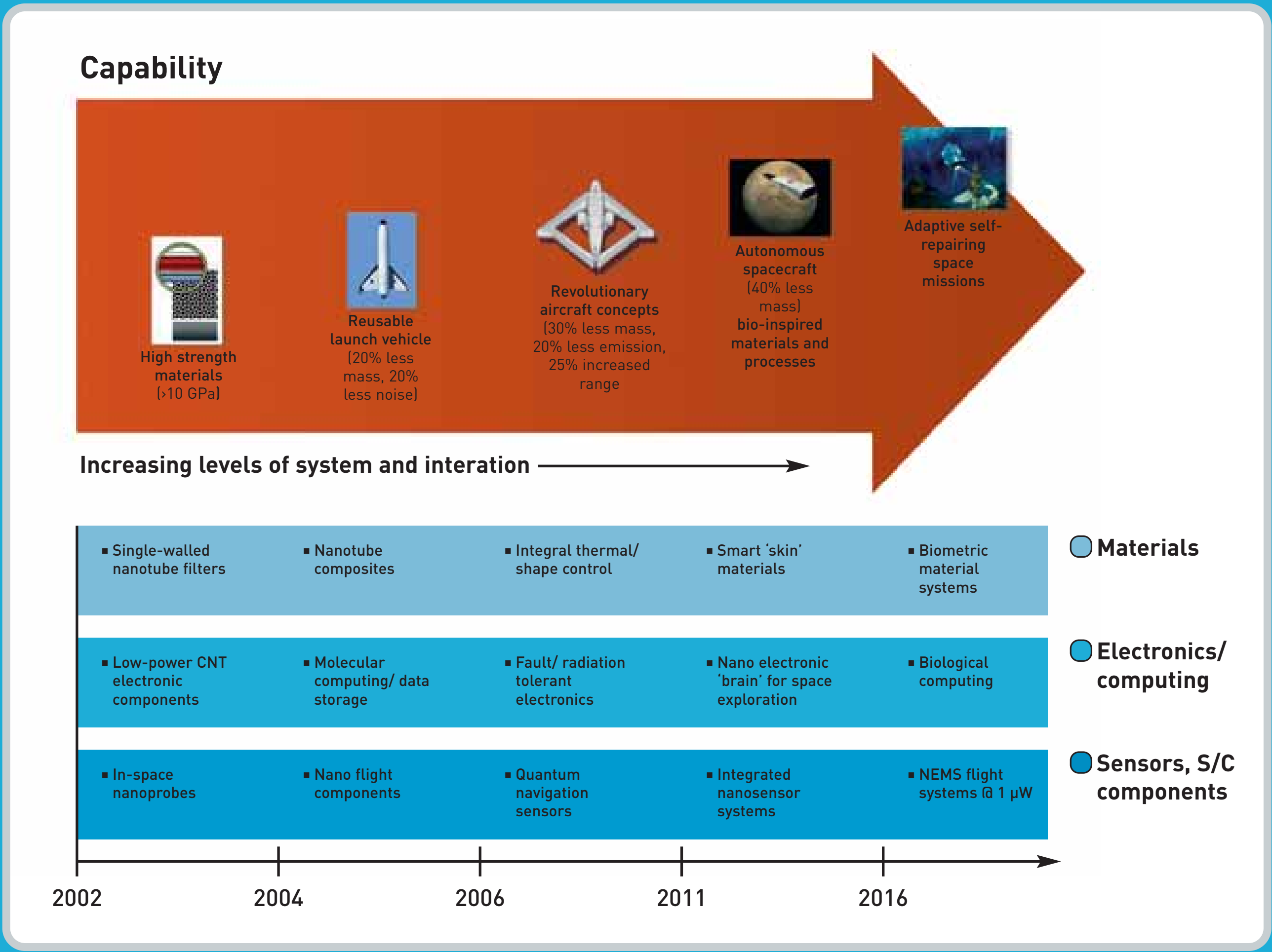
nanocomposites
materials, especially polymers, with a dispersion of nanoparticles (platelets, spheres, tubes, fibers) in order to create additional functions (strength, less fatigue, stiffness, conductivity, sensing and actuating functions)

nanofibers
fibers from various material with diameter on the nanoscale and having high mechanical strength potential

neutraceuticals
functional food, food with specific health/medical functions

NNI
National Nano Initiative (national nano research program of US government)

NRL
Navy Research Lab (USA)



Nasa Nanotechnology roadmap

ONR
Office of Naval Research (USA)

quantum dot
A quantum dot is a particle of matter so small that the addition or removal of an electron changes its properties in some useful way. All atoms are, of course, quantum dots, but multi-molecular combinations can have this characteristic. In biochemistry, quantum dots are called redox groups.

radar
em-radiation, typically in frequency domain 10-50 GHz for imaging and sensing

reactive armour
armour containing well-confined and distributed explosives to divert and deflect incoming ballistics

responsive packaging
packaging reacting to events and changing circumstances (switchable, color change, self signaling/alert for health condition etc)

RFID
Radio Frequency Identification, identify objects via wireless rf-systems consisting of RFID-tags with specified content and interrogators or readers supplying or reading radio energy (EM-waves) with modulated information

self-adaptive components
components and structures with integrated sensing and actuator capability in order to respond and adapt adequately to changing conditions and loads

self-configuring supply chain
highly automated and robotized supply chain based on wireless sensors, ID tags, (remote) programmable robot- and container vehicles

self-healing materials
materials with self-repair function (e.g. automated glue release upon fracture)

smart skin
adaptive, adjustable or stretchable skin (surface, color, texture, dimensions) for more functional devices and vehicles e.g. for stealth or better aerodynamics

smart textile
textile with integrated electronics, sensors, actuators, displays, biochemical absorbents, antennas etc or combinations

smart tires
tires with wireless pressure sensors and possibly in the future pressure adaptation capability to different terrains

tags, RFID
labels/tags on products, components, equipment for automated identification RFID is based on RF wireless reading for tracking, tracing and identification at remote small or large distances. Passive RFID tags hold read-only information, active RFID tags have more intelligence and can hold historical and sensory data.

tags, digital
electronic labels on data/information blocks for personalized retrieval, smart searching, limited access and security

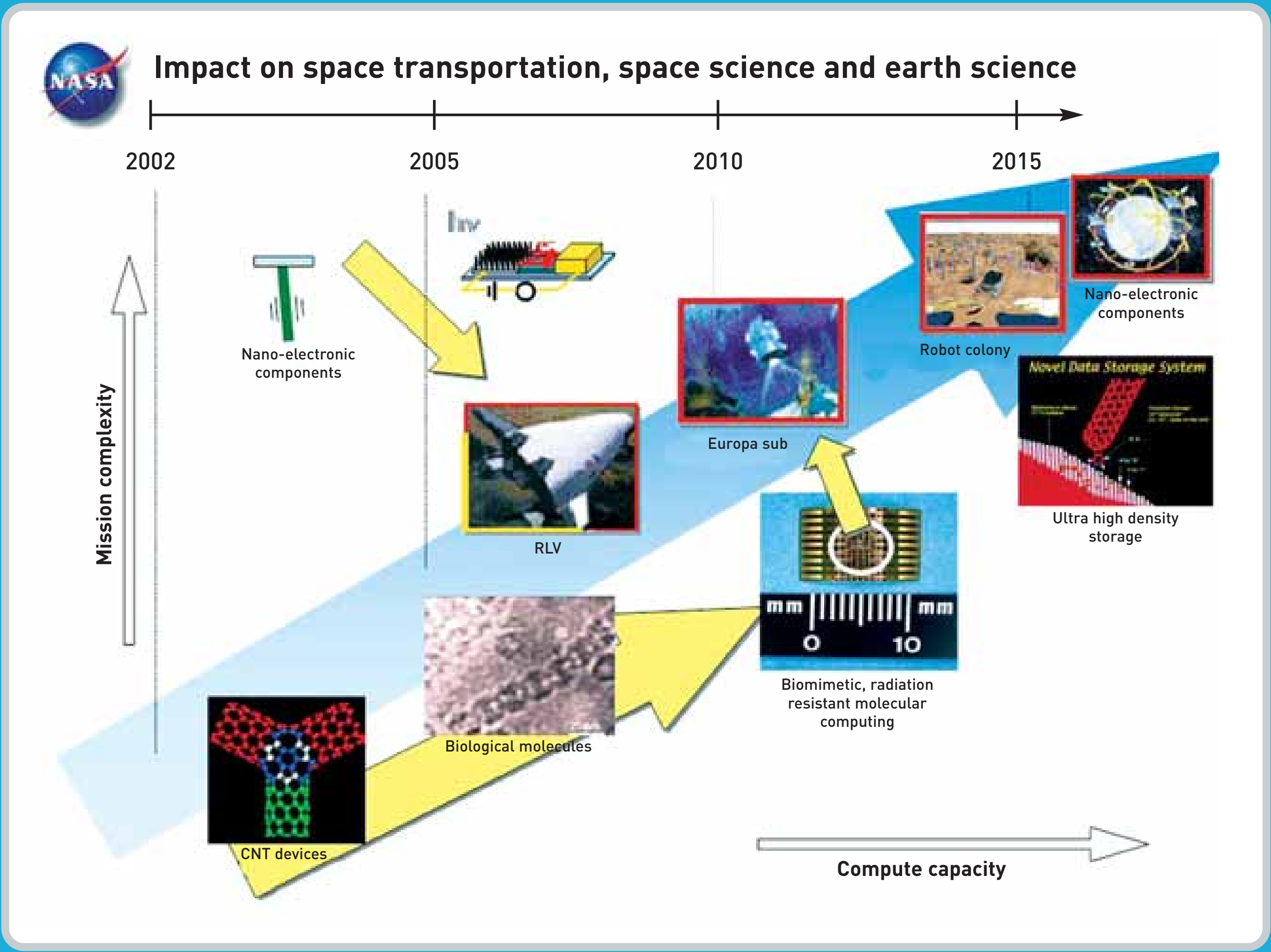
teleweapon
a remote (wireless) controlled weapon with sensing, targeting and firing options

teraHertz radiation
em-radiation in frequency domain 100 GHz- 30 THz, between infrared and microwave (wavelength 10 μ m – 3 mm), for high penetration imaging

tissue engineering
material and tools for self-repair of human tissue

UAV/UUV
unmanned aerial/underwater vehicle

Nano-electronics and computing roadmap



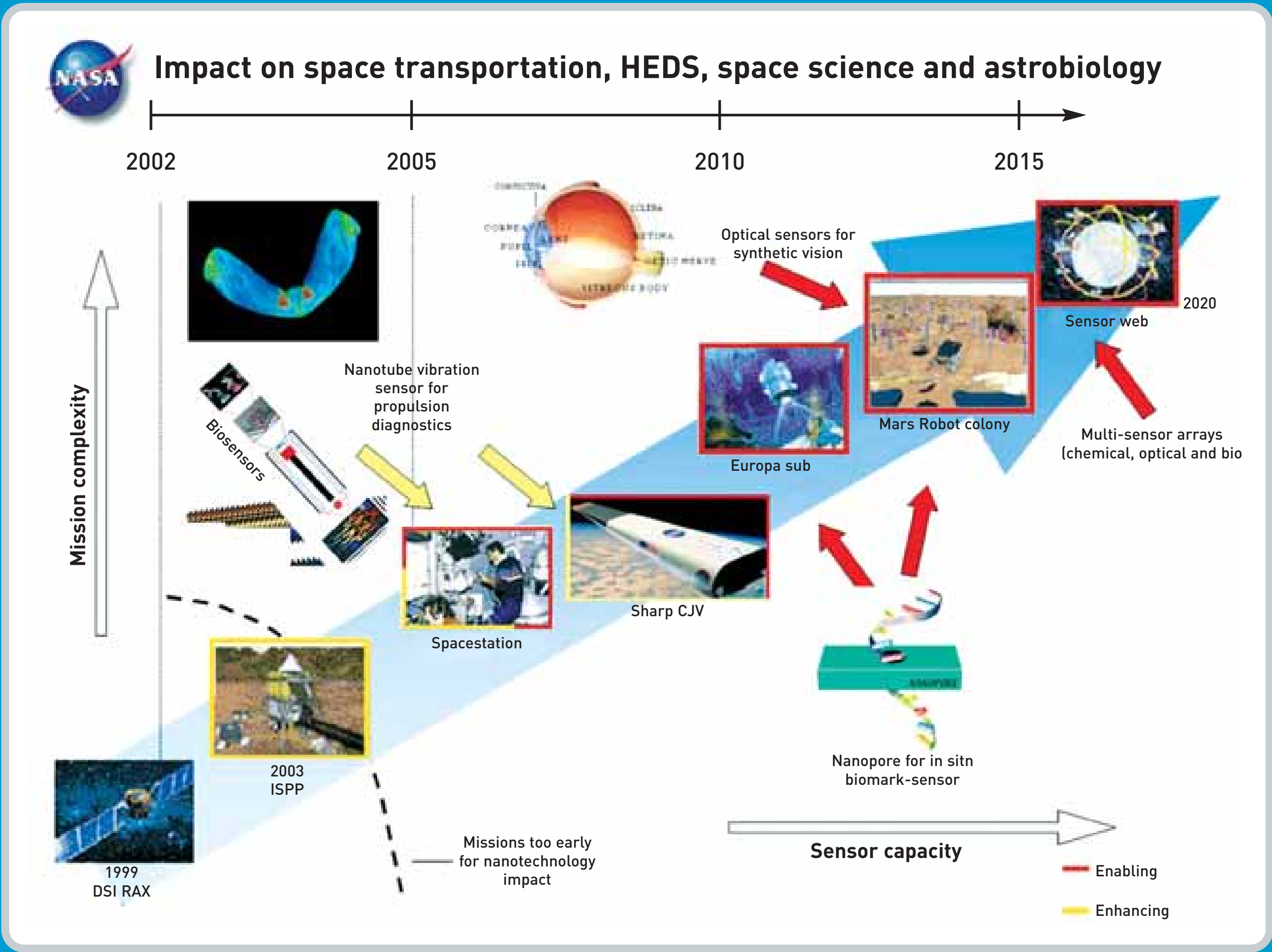
Nasa Nanoelectronics and Computing roadmap

Appendix II Cross reference list nanotechnologies

Based on the technology radars we have made a cross-reference list of all microsystems and nanotechnologies in the technology radars. The technologies have been divided into five main categories: Biology, Energy/power, Information and Materials. A first distinction has been made on the issues whether the technology has a principally offensive or defensive character. Secondly we indicate in the cross reference list whether the development of the technology is mainly civil or defence driven. Finally we assessed whether the technology is an improvement of an existing technology or a completely new, disruptive technology.

TECHNOLOGY	OFFENSIVE	DEFENSIVE	CIVIL	MILITARY	IMPROV.	NEW
BIOLOGY						
01. Biofluidic sensor		✪	✪		✪	
02. Membranes food		✪	✪		✪	
03. Tissue engineering		✪	✪			✪
04. Nutraceuticals		✪	✪		✪	
05. B/C protection		✪		✪	✪	
06. Implants		✪	✪		✪	
07. Targeted drug delivery		✪	✪		✪	
08. Artificial organs		✪	✪		✪	
09. Nerve muscle stimuli	✪	✪	✪	✪		✪
10. Biomimic Lightweight		✪	✪		✪	
11. Bio-mechanical hybrids	✪	✪		✪		✪
ENERGY / POWER						
01. Wearable power	✪	✪	✪			✪
02. µ-Power	✪	✪	✪			✪
03. µ-Fuel cell	✪	✪	✪			✪
04. Energy scavenging	✪	✪	✪			✪
05. µ-Fuel cell	✪	✪	✪			✪
06. µ- Nuclear battery	✪	✪	✪			✪
07. Biofuels		✪	✪		✪	
08. µ- Propulsion	✪	✪		✪	✪	
09. Droplet size injection		✪	✪		✪	
10. Nano cat / membranes		✪	✪		✪	
11. Micro laser	✪			✪		✪
12. µ- nuclear pellets	✪			✪	✪	
13. E-bombs	✪			✪		✪
14. Nano detonator	✪			✪	✪	
15. Hybrid power		✪	✪		✪	
16. Auto climate control		✪	✪		✪	

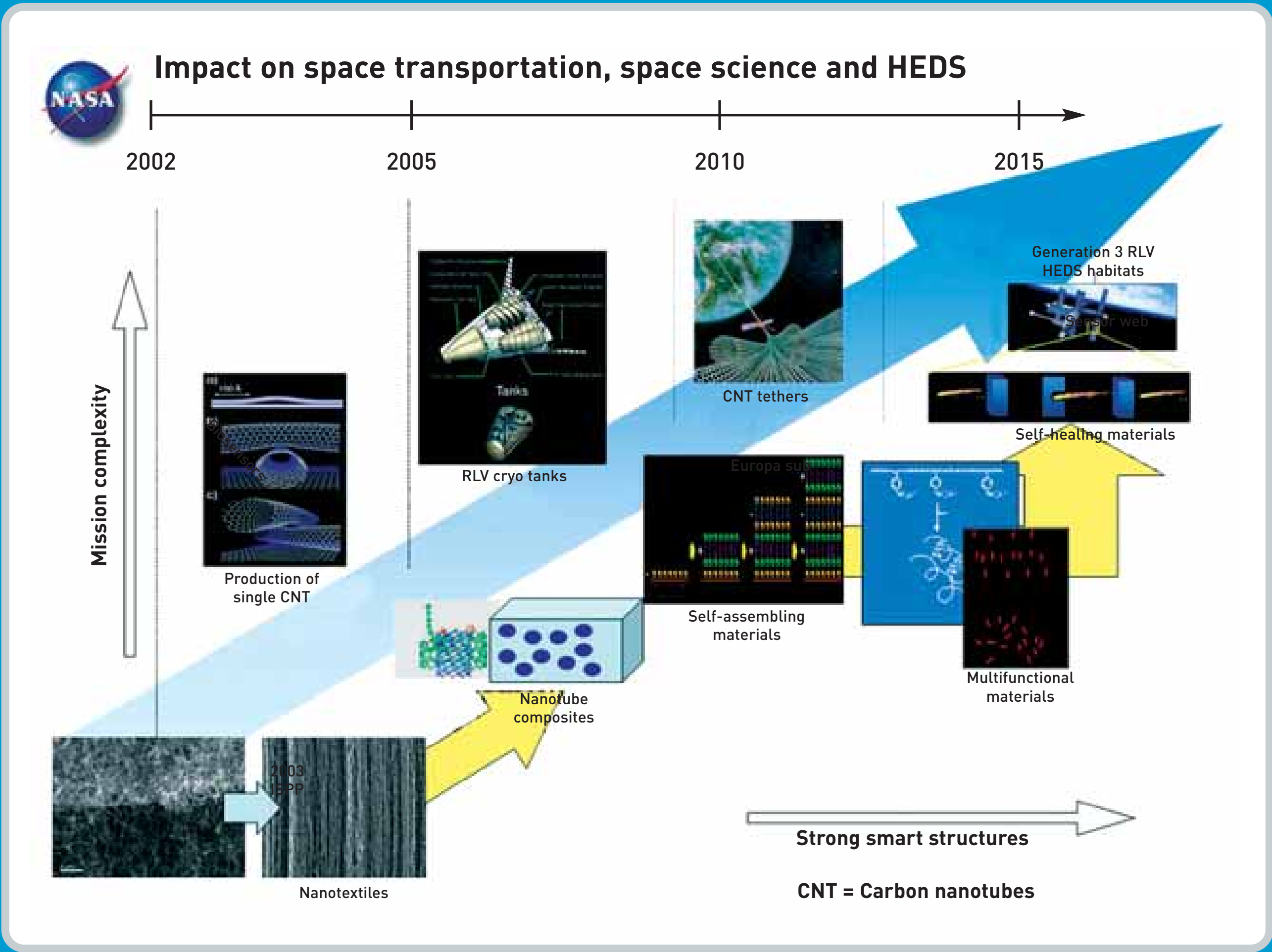
Nanosensors roadmap



Nasa Nanosensors roadmap

TECHNOLOGY	OFFENSIVE	DEFENSIVE	CIVIL	MILITARY	IMPROV.	NEW
INFORMATION						
01. PDA		✪	✪			✪
02. ID-Tags		✪	✪		✪	
03. μ Pos & motion. sensor	✪		✪	✪		✪
04. Biometric ID		✪	✪			✪
05. Wireless network	✪	✪	✪			✪
06. Ambient intelligence	✪	✪	✪			✪
07. Event driven info		✪	✪	✪		✪
08. Digital ID		✪	✪	✪	✪	
09. Digital tagging		✪	✪	✪	✪	
10. Self aggregating		✪	✪	✪		✪
11. μ Robots	✪	✪	✪	✪		✪
12. μ Radar - RF	✪	✪	✪		✪	
13. μ IR sensor	✪	✪		✪	✪	
14. Condition sensors		✪	✪		✪	
15. Teleweapon	✪			✪		✪
16. Safety/comfort sensors		✪	✪		✪	
17. μ-Sonar	✪	✪	✪		✪	
18. Biorobotics	✪	✪		✪		✪

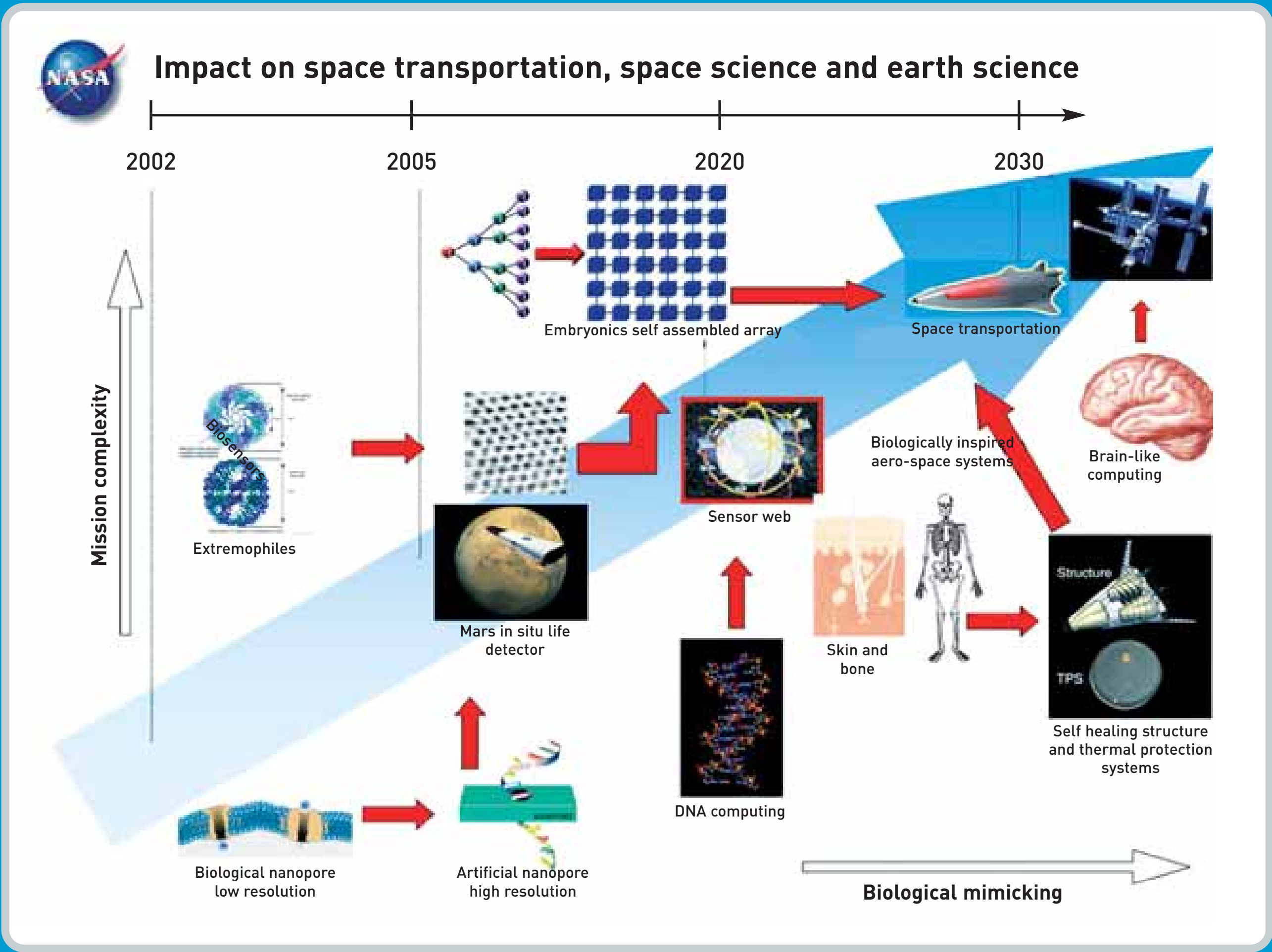
Nanomaterials roadmap



Nasa Nanomaterials roadmap

TECHNOLOGY	OFFENSIVE	DEFENSIVE	CIVIL	MILITARY	IMPROV.	NEW
MATERIALS						
01. Smart textiles		✪	✪			✪
02. Lightweight protective clothes		✪	✪	✪	✪	
03. Smart uniform		✪		✪		✪
04. Ambulant body sensing		✪	✪			✪
05. Flexible displays		✪	✪		✪	
06. 360° vision	✪	✪		✪	✪	
07. Exo-skeletons		✪		✪	✪	
08. Flexible/rigid materials		✪	✪	✪	✪	
09. Nanocomposites		✪	✪		✪	
10. Smart structures		✪	✪			✪
11. Lightweight materials		✪	✪		✪	
12. React nanoarmour		✪		✪	✪	
13. Self healing materials		✪	✪		✪	
14. Biomimic materials		✪	✪		✪	
15. High temperature plastics		✪	✪		✪	
16. Stealth materials	✪	✪		✪	✪	
17. Adaptive skin		✪	✪	✪		✪
18. Nanoassembly		✪	✪			✪

Biomimetics and bio-inspired systems



Nasa Biomimetics and Bio-inspired systems)

In this section a couple of specific nanotechnologies and their applications are being highlighted. This list is not complete yet and will be further expanded in future editions of this nanobook.

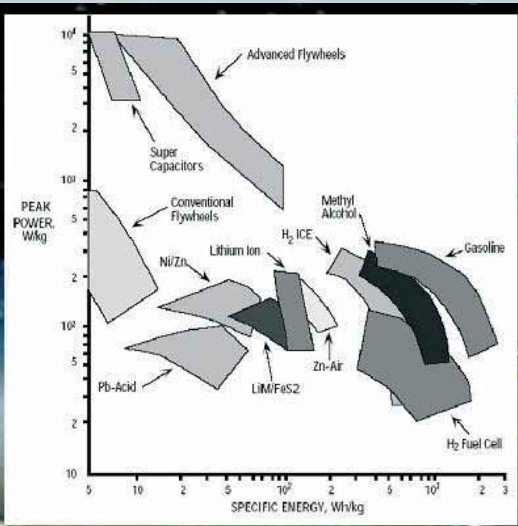
The technologies covered are:

- small and µ-power
- sensor tags
- nanosensors
- nanocomposites
- nanofibers by electrospinning

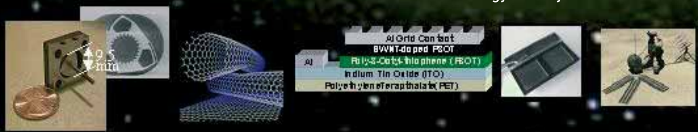
Small and μ power

Developments

- μ-international combustion engine (ICE)
- μ-printable battery
- CNT - H_2fuel cells
- Large area solar panels films, fibers
- Quantomdot solar cell
- Radio-isotope battery



Power vs energy density



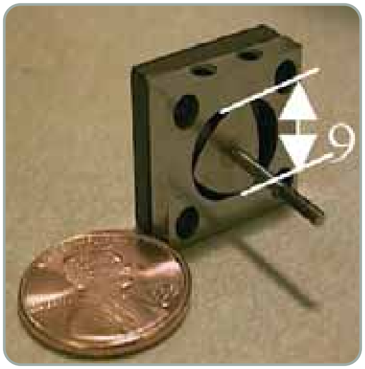
The future of wireless (nano or micro) sensor devices will very much depend upon the progress in miniaturisation of the power or energy supply. It is supposed to be one of the most critical issues for opening the high-volume market for wireless sensors.

Research in this area goes into various concepts depending on the required peak power and required long-term endurance of the energy pack. The following small-scale energy systems are in development:

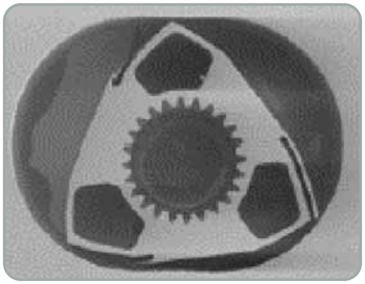
- high-peak power, short endurance
  - advanced flywheels (not nano)
  - super capacitors
- medium endurance, medium-peak power
  - various battery systems, nanotechnology assisted
  - flexible thin film batteries
- long endurance, low-peak power
  - H_2 fuel cells
  - µ-nuclear battery
- long endurance, medium-peak power
  - micro combustion engines

More and more effort goes into hybrid systems of rechargeable batteries and energy harvesting such as:

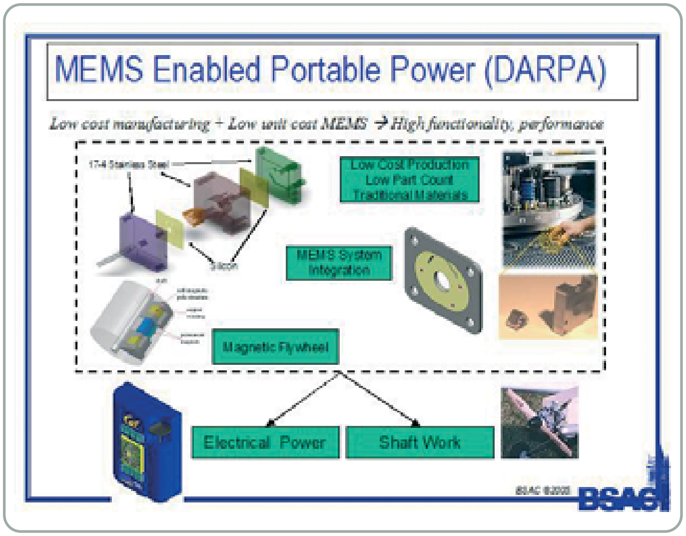
- solar-battery power pack: combined thin film battery with thin film solar cell
- remote charging with RF

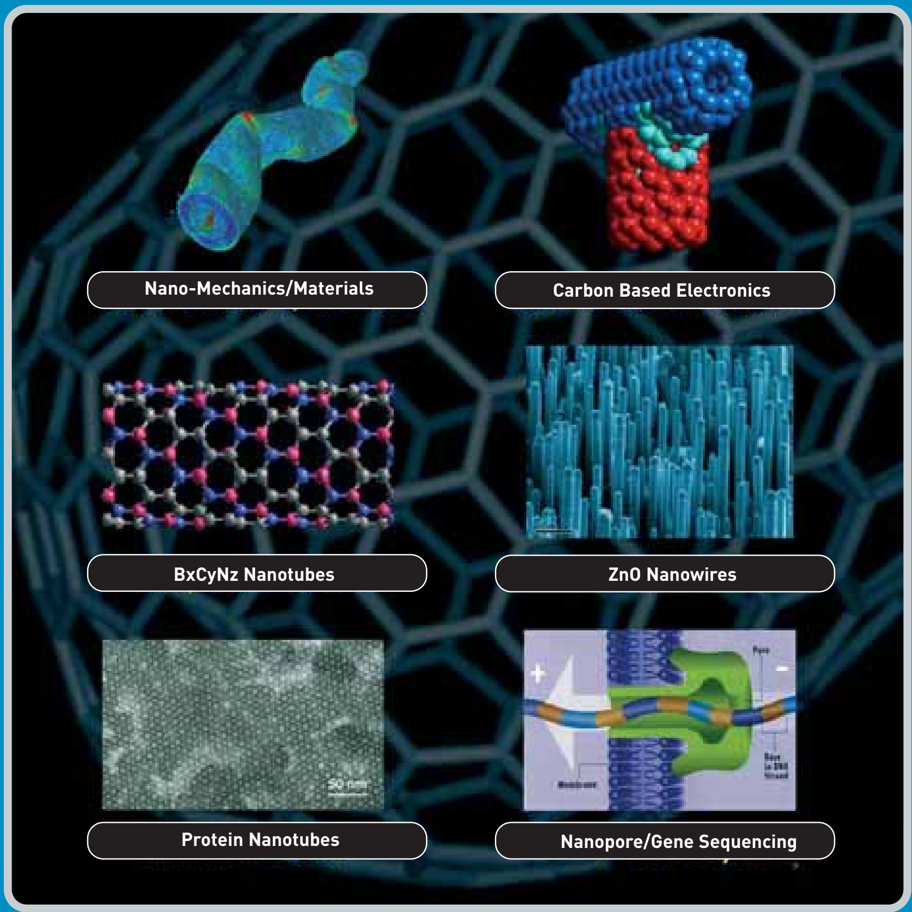


Portable power development of UC Berkeley for battery recharging and sensor systems



Combustion engines for kW power generation (5x5x5 cm) and for mW power generation (2.4 micron) in silicon.





Nano and biotechnology research of Nasa Ames

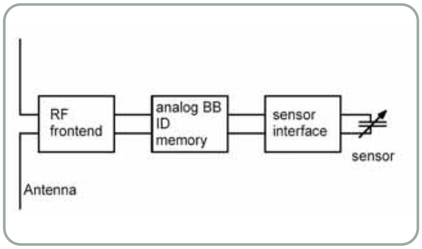
In the last 10 years RFID-technology has been developed to such a level that low-cost RFID-tagging has become reality for returnable transit items, expensive goods, access-control cards, passport, bankcards etc. Even individual item tagging is possible within a few years with ultra-low-cost UHF read only EPC tags and in 5-10 years all polymer-printed RFID-tags. Connected to this expected RFID roll-out there are in various market/product sector developing needs for sensor tags which can be wirelessly read via RF, optical or ultrasound devices and which give indicative values of the presence of certain substances near on the sensor tag or give reasonably accurate measurement of physical parameters such as temperature, pressure, moisture level etc. Sensor tags can be passive and will only measure when they are within the field of a rf-reader or an optical device. They can possibly harvest and retain power and by this will be able to measure at more moments. The last option is to equip them with film batteries to be able to sense critical values when needed and time-log them. To create sensor tags several technologies are or will become available:

- coupling of RFID passive Chips to sensors via sensor interfaces
- make passive capacitor circuits with reactive antenna substrates and dielectric materials (use conductive polymers, CNT's, nanowires)
- thin film batteries
- conductive, reactive polymers and functionalized nanomaterials (CNT's, nanowires, nanodots)
- silicon chips
- polymer logic.

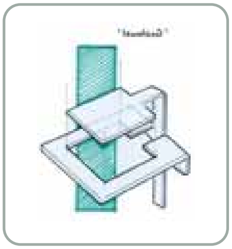
Ideally they have the size of a credit card, are flat and can be powered and read via a RFID-reader integrated in clothing, PDA, phone or watch. Sensor tags have potential application in the following areas:

- food processing
- food packaging
- personal protection of soldiers, first responders
- health monitoring (on skin for diabetic, implanted under skin, as wound dressings).

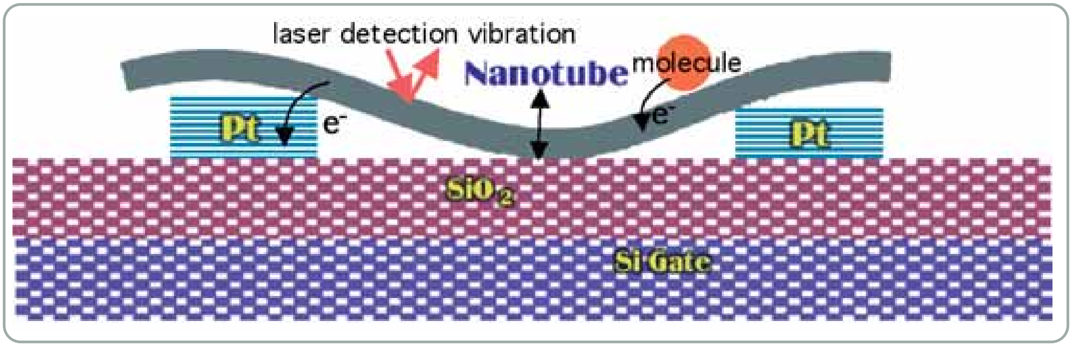
Sensor tag of Tagsense (start up from MIT)



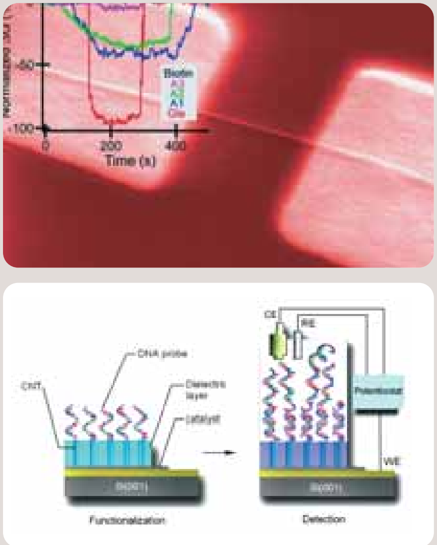
Basic construction sensor tag (VTT)



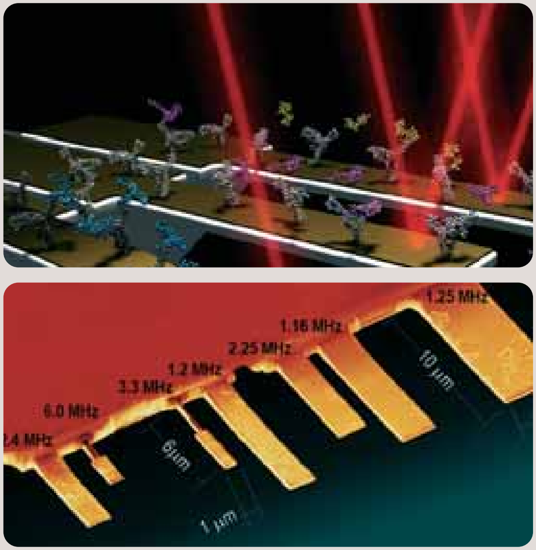
Senstenna (TNO)



Nanowire molecular sensor concept, NASA Ames: 1. electrochemical detection by electrical current
2. weight: change in mechanical resonance indicates molecular weight



DNA array: DNA probes on nanotubes
1. electrochemical detection
2. and/or fluorescence

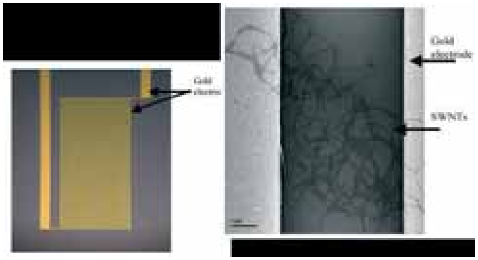


Electronic nose on chip, ppb/ppt gas/vapor detection
1. change in mechanical resonance by molecule absorption
2. detection via laser readout

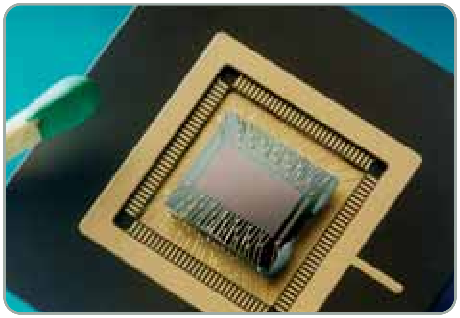
Nanotechnology has great potential for sensing devices since the nanoscale enables a high surface area coupled to a very low mass, featuring a high sensitivity and a high signal to noise ratio at a level that cannot be obtained on the macro scale. Also the high functional density and the ability to produce matrix-array sensors has many advantages.

The following sensing techniques on the nanoscale are being employed:

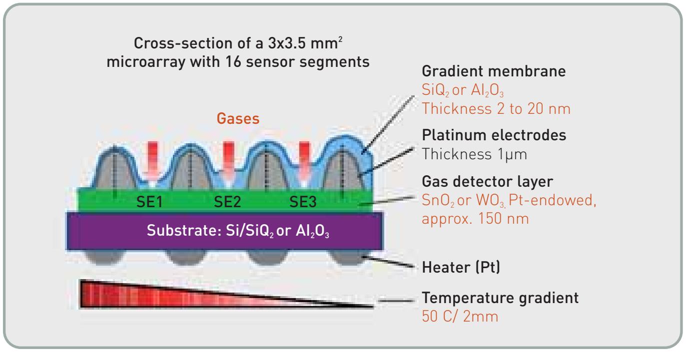
- mechanical resonators such as nano-cantilevers: the shift in resonance is a measure for the absorbed particle/ molecule
- optical resonators (optical cavity): resonance shift upon presence of change in optical index due to molecular absorption
- electrical/electrochemical: measuring charge transfer in contact with a nanowire, can be promoted with enzyme or catalyst
- electrical resistance: conductivity over a nano-porous (nanoparticles, nanofibers) substrate
- magnetic detection (GMR) via magnetic nanolabelling of molecules
- specific, targeted detection via DNA functionalized nanoparticles, with subsequent electrical or optical read-out
- single molecule detectors, enabled via quantumdot fluorescent labeling
- lab-on-chip systems for processing, upconversion and detection of DNA and proteomics

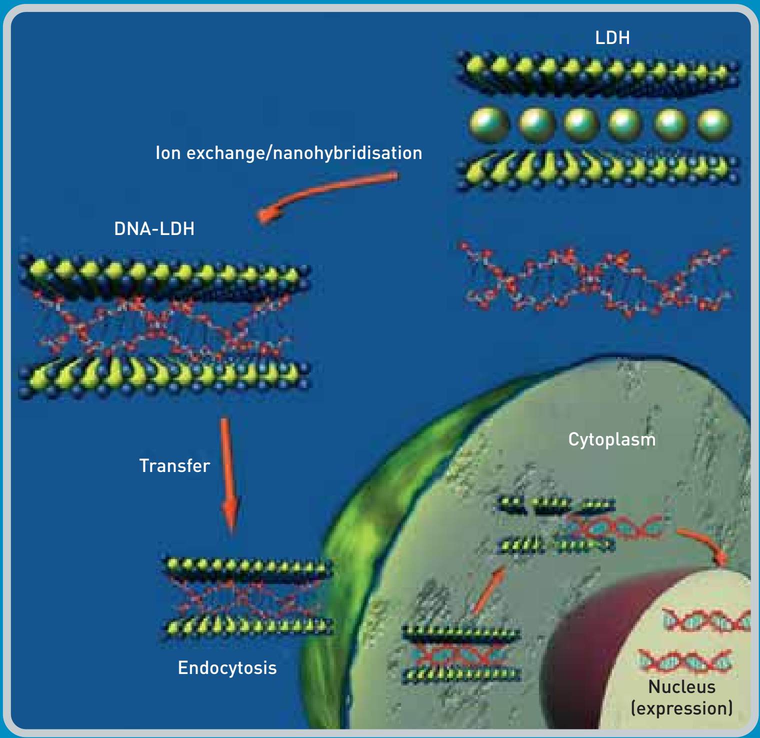


Chemiresistor with cnt's or nanofiber fabric, for gases (NASA Ames)



MOx gradient matrix gas sensor, ppb level, ForschungsZentrum Karlsruhe



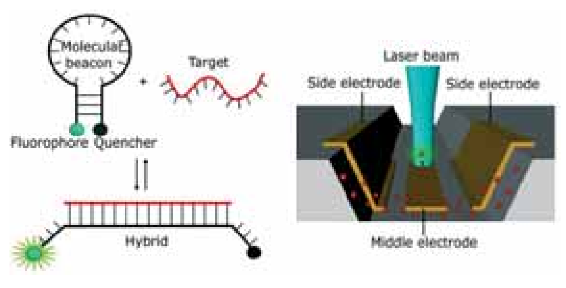

LDH
Ion exchange/nanohybridisation
DNA-LDH
Transfer
Cytoplasm
Endocytosis
Nucleus
(expression)

The ageing population, the high expectations for better quality of life and the changing lifestyle of society lead to the need for improved, more efficient, and affordable health care. Nanomedicine is defined as the application of nanotechnology in medicine. It exploits the improved and often novel physical, chemical, and biological properties of materials on the nanometric scale. Nanomedicine has a potential impact on the prevention, early and reliable diagnosis and treatment of diseases. In nanomedicine, three areas are of special interest:

- **Nano-diagnostics, including medical imaging, for identification and diagnosis at the earliest stage possible**
  - highly sensitive, preferably single-molecule, detection of (early) biomarkers
  - high-resolution microscopic and spectroscopic techniques, both in-vitro as well as in-vivo
  - high-resolution in-vivo imaging techniques such as MRI, CT, PET and Ultrasound
  - target-specific contrast nanostructures for imaging
  - theranostics: combination of diagnostic (targeted contrast agents) with therapeutic molecules (e.g. radio isotopes)

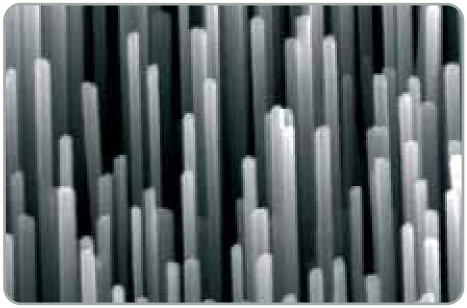
- **Targeted drug-delivery and controlled release**
  - drug-delivery microchip technology, implantable (e.g. automated glucose delivery)
  - nanoparticles that can release on demand pharmaceuticals, triggered by bioreaction or by external forces
  - dna loaded nanoparticles that can be transfected into cells to repair malfunctioning of cells

- **Regenerative medicine, tissue engineering**
  - in-situ tissue regeneration and repair with bioactive (dna carrying) particles that induce specific cell growth
  - biomimic nanostructures to be used in scaffolds for optimal tissue uptake and regeneration

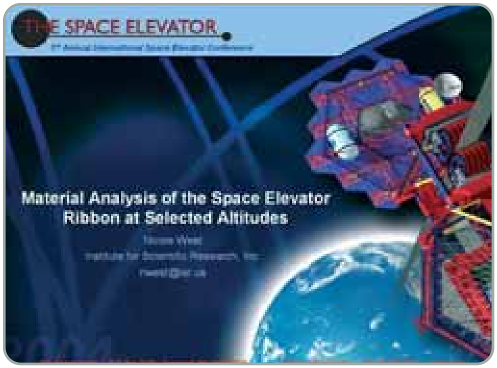


Single molecule detection (dna, proteomics)
by Jeff Wang, Johns Hopkins Univ, USA

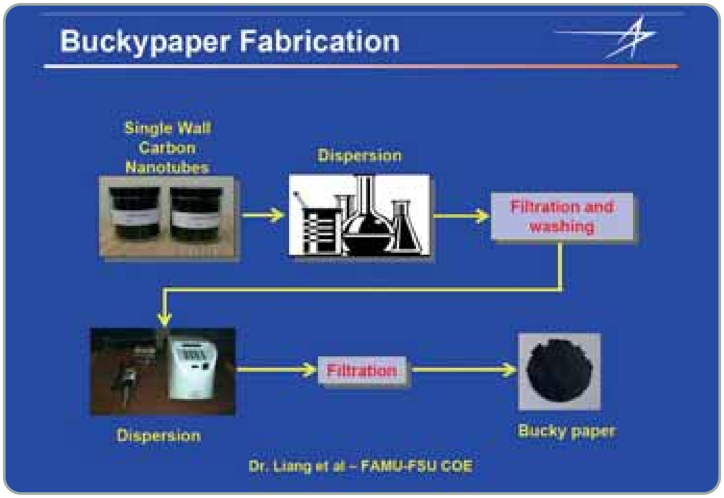
Nanoclay reinforced elastomers for improved gas barrier properties (e.g. TNO)



Vapor phase grown carbon nanotubes



Space elevator project (USA): Goal is to develop a 60% CNT filled polymer (PMMA or PS) with an exceptional tensile strength of 60 GPa. Current status for these composites is 2-4 GPa Existing high strength fibers such as carbon fiber, aramide, dyneema, PBO are in the range of 3-6 GPa.



High strength carbon nanotube laminate (bucky paper) for high strength lightweight aerospace structures.

Nanocomposites: materials with superior properties

Nanocomposites consist of a matrix material, usually a polymer, with a dispersion of nanoparticles in order to enhance mechanical, electrical or chemical properties. The nanoparticles create an enormous surface area inside the matrix material, thus affecting the overall properties. Good dispersion, interfacial bonding to the matrix, orientation and alignment are the major technological challenges in order to achieve the desired material improvements. Various types of nanoparticles are on the market, ranging from spherical, platelets, tubes to fibers.

Nanotubes: carbon nanotubes (CNT), single-wall nanotubes (SWNT), double- and multi-wall nanotubes (DWNT, MWNT)
With carbon nanotubes (diameter 1-2 nm, aspect ratio 10^3,10^4) the following ultimate material properties are foreseen:

- mechanical: elastic modulus up to 1-5 MPa, ultimate tensile strength: 30-180 GPa
- electrical conductivity: 6000 S/cm, thermal conductivity: 2000 W/mK
- ultrahigh surface area: 1500 m^2/gram

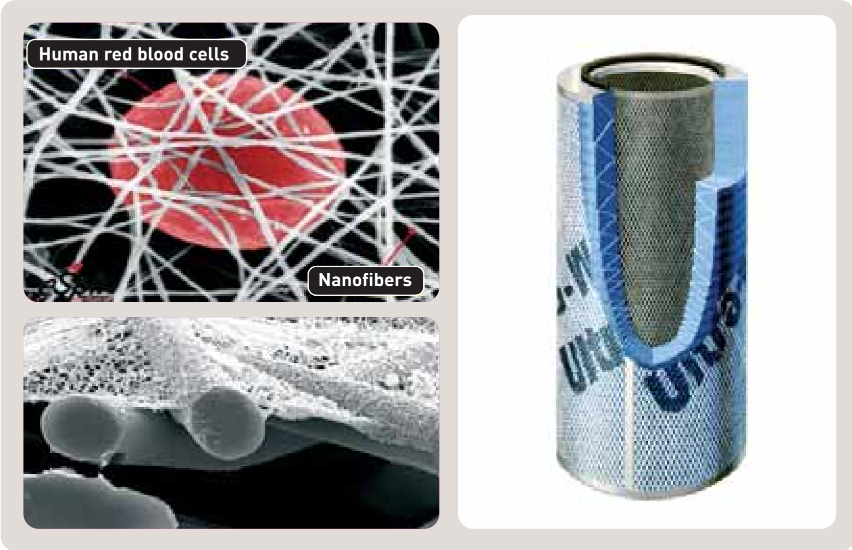
Up to now, the exceptional tensile strength properties have not been realized yet, at present only 1-2 percent of the potential strength has been realized. But a lot of effort is still being made in order to improve matrix bonding, orientation etc.

Nanoplatelets: graphite (GNP), nanoclay; exfoliated nanoclay platelets
Nanoplatelets (thickness 1-2 nm, aspect ratio 10^2, 10^3) are relatively low-cost nanoadditives (5-10 $/kg) and are being applied in order to:

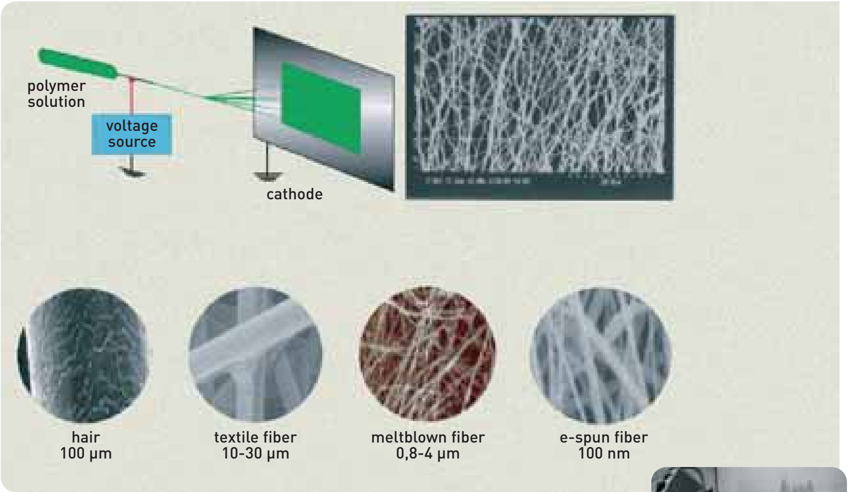
- increase chemical, UV and thermal stability (usually 50 to 100 K up)
- increase fracture toughness: typically a factor 10^3
- increase tensile strength: factor 2
- diffusion barrier: factor 2-10

Nanofiber: vapour-phase-grown graphite (VGNF. pyrograf); electrospun nanofibers, phase-separated liquid crystal fibers
Nanofibers can be electrospun out of any polymer. First application is in nano-filtering systems. Mechanical properties have not been very well researched so far. With orientated nanofibers high mechanical strength is to be expected.

Nanocomposite nanofibers: organic co-polymer co-electrospun with CNT's; inorganic matrix reinforced with CNT's etc. Nanocomposite nanofibers are at a very early stage of development. The goal is to achieve very high-strength fibers. This seems to be a long-term development.



Nanofiber respiration filter and nonwoven nanofiber filter fabric (eSpin, USA).



High throughput electrospinning of nanofibers (Tandec, USA)

Nanofibers by electrospinning

Electrospinning is a cheap and relatively simple technique to produce nanofibers. The technique is very old but has regained interest since it enables the production of cheap nanostructures. The process simply consists of:

- blowing a polymer solution through a small nozzle
- applying a high voltage (25 - 50 kV) over nozzle and substrate to reduce the fiber diameter electrostatically down nanoscale
- recollect the nonwoven nanofiber mat from the substrate

Other characteristics are:

- typical fiber diameters are in the range of 50 – 200 nm
- long fibers: typically cm range
- also suited to produce ceramic, metaloxide and carbon nanofibers
- high throughput

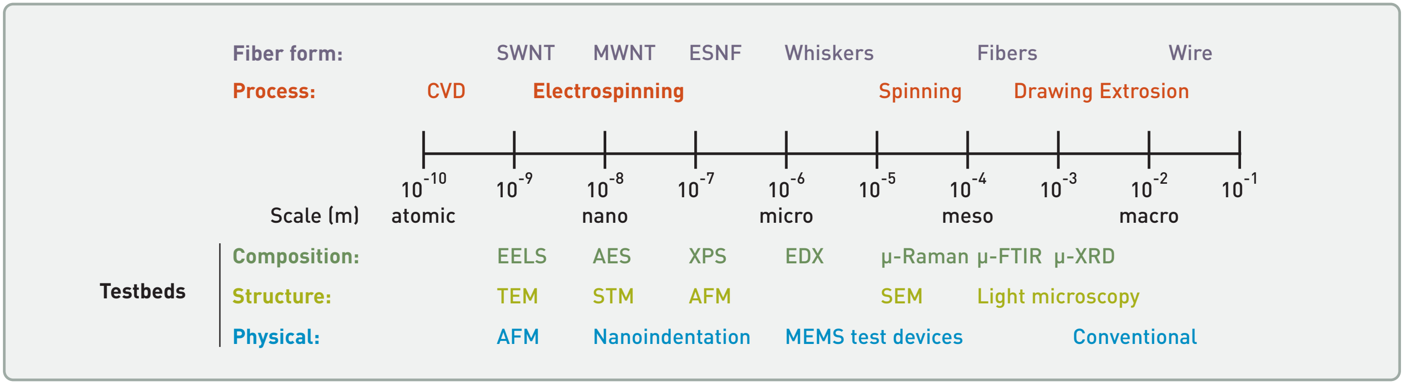
Nanofibers can be used in nonwoven mats but can also be spun into yarn. The following applications are in development:

- nanofiltration and absorption (see eSpin, USA)
- catalytic breakdown (catalytic active nanofiber, or nanofibers with a catalytic coating, BC breakdown)
- sensors, thanks to the large surface area sensitive to absorption and subsequent change in e.g. electrical resistance (polymer conductive nanofiber) to be investigated:
  - structural applications, reinforcement fiber, e.g. for anti-ballistics
  - insulation
  - selective gas permeation (breathing, BC protective fabric)
  - carbon nanotube polymer composite fiber (high strength)

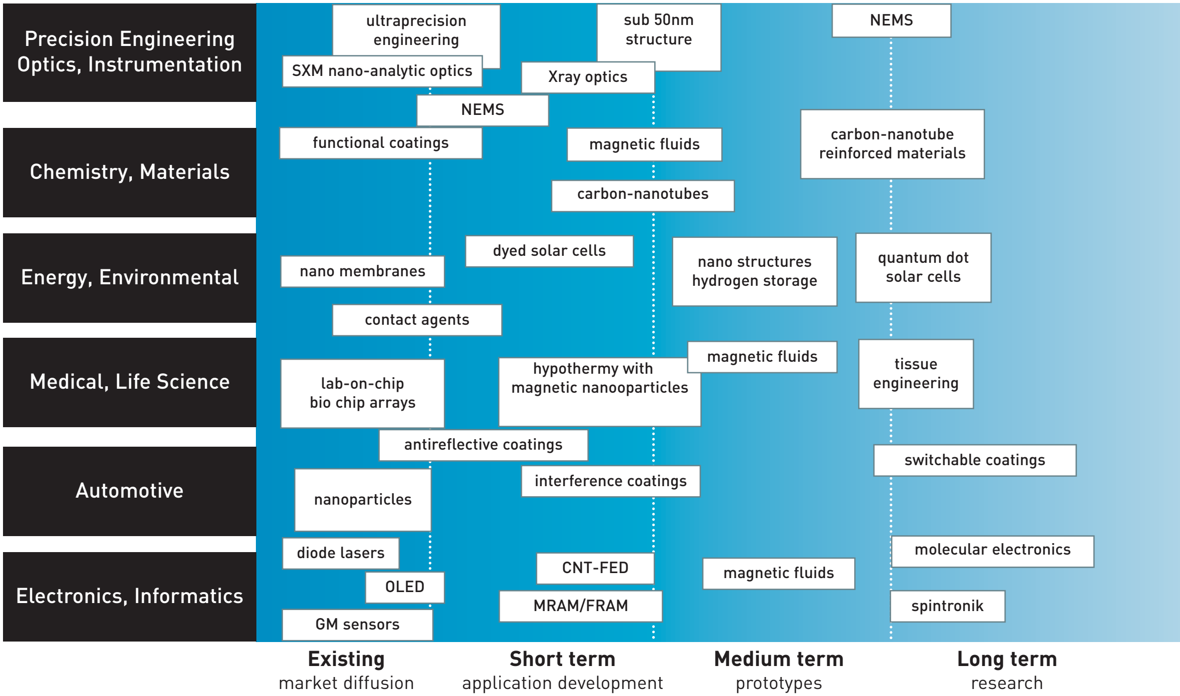
Tensile strength

The tensile strength of nanofibers has not been researched much. First experiments with nonwoven mats indicate that the tensile strength increases significantly with reduction of the fiber diameter: e.g. going from a 6 μm fiber to a 60 nm fiber resulting in a 10-fold tensile strength. The increase is expected to originate from:

- increase in number fiber-to-fiber bonds
- orientation of the polymeric molecules in the fiber-length direction



Status and applications of nanotechnology (VDI technologiezentrum GmbH)



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