NASA applications of molecular nanotechnology

Al Globus, David Bailey, Jie Han, Richard Jaffe, Creon Levit, Ralph Merkle, and Deepak Srivastava

Published in *The Journal of the British Interplanetary Society*, volume 51, pp. 145-152, 1998.

Abstract

Laboratories throughout the world are rapidly gaining atomically precise control over matter. As this control extends to an ever wider variety of materials, processes and devices, opportunities for applications relevant to NASA's missions will be created. This document surveys a number of future molecular nanotechnology capabilities of aerospace interest. Computer applications, launch vehicle improvements, and active materials appear to be of particular interest. We also list a number of applications for each of NASA's enterprises. If advanced molecular nanotechnology can be developed, almost all of NASA's endeavors will be radically improved. In particular, a sufficiently advanced molecular nanotechnology can arguably bring large scale space colonization within our grasp.

Introduction

This document describes potential aerospace applications of molecular nanotechnology, defined as the thorough three-dimensional structural control of materials, processes and devices at the atomic scale. The inspiration for molecular nanotechnology comes from Richard P. Feynman's 1959 visionary talk at Caltech in which he said, "The problems of chemistry and biology can be greatly helped if our ability to see what we are doing, and to do things on an atomic level, is ultimately developed---a development which I think cannot be avoided." Indeed, scanning probe microscopes (SPMs) have already given us this ability in limited domains. See the IBM Almaden STM Gallery for some beautiful examples. Synthetic chemistry, biotechnology, "laser tweezers" and other developments are also bringing atomic precision to our endeavors.

[Drexler 92a], an expanded version of Drexler's MIT Ph.D. thesis, examines one vision of molecular nanotechnology in considerable technical detail. [Drexler 92a] proposes the development of programmable molecular assembler/replicators. These are atomically precise machines that can make and break chemical bonds using mechanosynthesis to produce a wide variety of products under software control, including copies of themselves. Interestingly, living cells exhibit many properties of assembler/replicators. Cells make a wide variety of products, including copies of themselves, and can be programmed with DNA. Replication is one approach to building large systems, such as human rated launch vehicles, from molecular machines manipulating matter one or a few atoms at a time. Note that biological replication is responsible for systems as large as redwood trees and whales.

Another approach to nanotechnology is supramolecular self-assembly, where molecular systems are designed to attract each other in a particular orientation to form larger systems. Hollow spheres large enough to be visible in a standard light microscope have been created this way using self-assembling lipids. There are many other examples and this field is rapidly advancing. Biological systems can do most of what molecular nanotechnology strives to accomplish -- atomically precise products, active materials, reproduction, etc. However, biological systems are extremely complex and molecular nanotechnology seeks simpler systems to understand, control and manufacture. Also, biological systems usually work at fairly mild temperature and pressure conditions in solution -- conditions that are not found in most aerospace environments.

Today, extremely precise atomic and molecular manipulation is common in many laboratories around the world and our abilities are rapidly approaching Feynman's dream. The implications for aerospace development are profound and ubiquitous. A number of applications are mentioned here and a few are described in some detail with references. From this sample of applications it should be clear that although molecular nanotechnology is a long term, high risk project, the payoff is potentially enormous -- vastly superior computers, aerospace transportation, sensors and other technologies; technologies that may enable large scale space exploration and colonization.

This document is organized into two sections. In the first, we examine three technologies -- computers, aerospace transportation, and active materials -- useful to nearly all NASA missions. In the second, we investigate some potential molecular nanotechnology payoffs for each area identified in NASA's strategic plan. Some of these applications are under investigation by nanotechnology researchers at NASA Ames. Some of the applications described below have relatively near-term potential and working prototypes may be realized within three to five years. This is certainly not true in other cases. Indeed, many of the possible applications of nanotechnology that we describe here are, at the present time, rather speculative and futuristic. However, each of these ideas have been examined at least cursorily by competent scientists, and as far as we know all of them are within the bounds of known physical laws. We are not suggesting that their achievement will be easy, cheap or near-term. Some may take decades to realize; some other ideas may be scrapped in the coming years as insuperable barriers are identified. But we feel that they are worth mentioning here as illustrations of the potential future impact of nanotechnology.

Technology

Computer Technology

The applicability of manufacturing at an ever smaller scale is nowhere more self-evident than in computer technology. Indeed, Moore's law [Moore 75] (an observation not a physical law) says that computer chip feature size decreases exponentially with time, a trend that predicts atomically precise computers by about 2010-2015. This capability is being approached from many directions. Here we will concentrate on those under development by NASA Ames and her partners. For a review of many other approaches see [Goldhaber-Gordon 97].

Carbon Nanotube SPM Tips

Carbon nanotubes [Iijima 91] can be viewed as rolled up sheets of graphite from 0.7 to many nanometers in diameter. The smaller tubes are single molecules. [Dai 96] placed carbon nanotubes on an SPM tip thus extending our ability to manipulate a single molecule with sub-angstrom accuracy. Not only are the tips atomically precise, but they should have approximately the same chemistry as C_{60}, and thus be functionalizable with a wide variety of molecular fragments [Taylor 93]. Functionalizing carbon nanotube tips will allow mechanical manipulation of many molecular systems on various surfaces with sub-angstrom accuracy.

One particularly intriguing possibility along this line is to utilize a carbon nanotube SPM tip to engrave patterns on a silicon surface. It should be possible to create features a few nanometers across. These would be perhaps 100 times finer than the current state of the art in commercial semiconductor photolithography. Further, in contrast to approaches such as electron microscope lithography for which the speed of operation now appears to be an insuperable obstacle for industrial production, nanotube SPM-based lithography can be accelerated by utilizing an array with thousands of SPM tips simultaneously engraving different parts of a silicon surface. Also, nanotube SPM lithography could provide a practical means to explore various futuristic electronic device technology ideas, such as quantum cellular automata, which require exceedingly small feature sizes. Needless to say, if these ideas pan out, they could literally revolutionize computer device technology, paving the way for systems that are many times more powerful and more compact than any available today.

For the near term, it should be noted that the semiconductor industry is a major market for SPM products. These are used to examine production equipment. High performance carbon nanotube tips should be of substantial value. NASA Ames is collaborating with Dr. Dai, now at Stanford, to develop these tips.

Data Storage on Molecular Tape

It is possible to store data on long chain molecules (for example, DNA) and it may be possible to read these data with carbon nanotube tipped SPMs. Existing DNA synthesis techniques can be used to write data. If the different DNA base pairs can be distinguished with a carbon nanotube tipped SPM, then the data can be read non-destructively (current techniques allow a destructive read). However, the difference between base pairs is not great. If the base pairs cannot be distinguished, techniques for attaching modified enzymes to specific base pair sequences [Smith 97] could be used. Certain enzymes (DNA (cytosine-5) methyltransferases) attach themselves onto a specific sequence of base pairs with a covalent bond. The enzyme then performs its operation and breaks the bond. [Smith 97] modified the enzyme such that the initial covalent bond was formed but the subsequent operation was disrupted. The result is that DNA synthesized with the target base pair sequences at the desired location can force precise placement of the enzymes. The presence of an enzyme could represent 1 and its absence 0. Enzymes are sufficiently large that distinguishing their presence should be straightforward. If the DNA/enzyme approach proves impossible, a wide variety of other polymer systems could be examined.

Data Storage on Diamond

[Bauschlicher 97a] computationally studied storing data in a pattern of fluorine and hydrogen atoms on the (111) diamond surface (see figure). If write-once data could be stored this way, 10^{15} bytes/cm^2 is theoretically possible. By comparison, the new DVD write-once disks now coming on the market hold about 10^8 bytes/cm^2. [Bauschlicher 97a] compared the interaction of different probe molecules with a one dimensional model of the diamond surface. This study found some molecules whose interaction energies with H and F are sufficiently different that the force differential should be detectable by an SPM. These studies were extended to include a two dimensional model of the diamond surface and two other systems besides F/H [Bauschlicher 97b]. Other surfaces, such as Si, and other probes, such as those including transition metal atoms, have also been investigated [Bauschlicher 97c].

Among the better probes was C_5H_5N (pyridine). Quantum calculations suggest that pyridine is stable when attached to C60 in the orientation necessary for sensing the difference between hydrogen and fluorine. Half of C_{60} can form the end cap of a (9,0) or (5,5) carbon nanotube, and carbon nanotubes have been attached to an SPM tip [Dai 96]. Thus, it might be possible using today's technology to build a system to read the diamond memory surface.

[Avouris 96] has shown that individual hydrogen atoms can be removed from a silicon surface. If this could be accomplished in a gas that donates fluorine to vacancies on a diamond surface, the data storage system could be built. [Thummel 97] computationally investigated methods for adding a fluorine at the radical sites where a hydrogen atom had been removed from a diamond surface.

Carbon Nanotube Electronic Components

As mentioned before, carbon nanotubes can be described as rolled up sheets of graphite. Different tubes can have different helical windings depending on how the graphite sheet is connected to itself. Theory [Dresselhaus 95, pp. 802-814] suggests that single-walled carbon nanotubes can have metallic or semiconductor properties depending on the helical winding of the tube. [Chico 96], [Han 97b], [Menon 97a], [Menon 97b], and others have computationally examined the properties of some of hypothetical devices that might be made by connecting tubes with different electrical properties. Such devices are only few nanometers across -- 100 times smaller than current computer chip features. For a number of references in fullerene nanotechnology see [Globus 97].

Molecular Electronic Components

Several authors, including [Tour 96], have described methods to produce conjugated macromolecules of precise length and composition. This technique was used to produce molecular electronic devices in mole quantities [Wu 96]. The resultant single molecular wires were tested experimentally and found to be conducting [Bumm 96]. The three and four terminal devices have been examined computationally and look promising [Tour 97]. The features of these components are approximately 3 angstroms wide, about 750 times smaller than current silicon technology can produce.

Helical Logic

From [Merkle 96]:

> Helical logic is a theoretical proposal for a future computing technology using the presence or absence of individual electrons (or holes) to encode 1s and 0s. The electrons are constrained to move along helical paths, driven by a rotating electric field in which the entire circuit is immersed. The electric field remains roughly orthogonal to the major axis of the helix and confines each charge carrier to a fraction of a turn of a single helical loop, moving it like water in an Archimedean screw. Each loop could in principle hold an independent carrier, permitting high information density. One computationally universal logic operation involves two helices, one of which splits into two "descendant" helices. At the point of divergence, differences in the electrostatic potential resulting from the presence or absence of a carrier in the adjacent helix controls the direction taken by a carrier in the splitting helix. The reverse of this sequence can be used to merge two initially distinct helical paths into a single outgoing helical path without forcing a dissipative transition. Because these operations are both logically and thermodynamically reversible, energy dissipation can be reduced to extremely low levels. ... It is important to note that this proposal permits a single electron to switch another single electron, and does not require that many electrons be used to switch one electron. The energy dissipated per logic operation can likely be reduced to less than 10^{-27} joules at a temperature of 1 Kelvin and a speed of 10 gigahertz, though further analysis is required to confirm this. Irreversible operations, when required, can be easily implemented and should have a dissipation approaching the fundamental limit of ln 2 x kT.

Rod Logic

One study not conducted by Ames or partners is particularly worth mentioning since it places a loose lower bound on the computational capabilities of molecular nanotechnology. [Drexler 92a] designed a number of computer components using small diamondoid rods with knobs that allow or prevent movement to accomplish computation. While this tiny mechanical Babbage Machine is probably not an optimal computational engine, its calculated performance for a desktop computer is 10^{18} MIPS -- about a million times more powerful than the largest supercomputer that exists today (Fall 1997).

Note that with very fast computation energy use and heat dissipation become a severe problem. One approach to addressing this issue is reversible logic.

Aerospace Transportation

Launch Vehicles

[Drexler 92a] proposed a nanotechnology based on diamond and investigated its potential properties. In particular, he examined applications for materials with a strength similar to that of diamond (69 times strength/mass of titanium). This would require a very mature nanotechnology constructing systems by placing atoms on diamond surfaces one or a few at a time in parallel. Assuming diamondoid materials, [McKendree 95] predicted the performance of several existing single-stage-to-orbit (SSTO) vehicle designs. The predicted payload to dry mass ratio for these vehicles using titanium as a structural material varied from < 0 (the vehicle won't work) to 36%, i.e., the vehicle weighs substantially more than the payload. With hypothetical diamondoid materials the ratios varied from 243% to 653%, i.e., the payload weighs far more than the vehicle. Using a very simple cost model ($1000 per vehicle kilogram) sometimes used in the aerospace industry, he estimated the cost per kilogram launched to low-Earth-orbit for diamondoid structured vehicles should be $153-412. This would meet NASA's 2020 launch to orbit cost goals. Estimated costs for titanium structured vehicles varied from $16,000-59,000/kg. Although this cost model is probably adequate for comparison, the absolute costs are suspect.

[Drexler 92b] used a more speculative methodology to estimate that a four passenger SSTO weighing three tons including fuel could be built using a mature nanotechnology. Using McKendree's cost model, such a vehicle would cost about $60,000 to purchase -- the cost of today's high-end luxury automobiles.

These studies assumed a fairly advanced nanotechnology capable of building diamondoid materials. In the nearer term, it may be possible to develop excellent structural materials using carbon nanotubes. Carbon nanotubes have a Young's modulus of approximately one terapascal -- comparable to diamond. Studies of carbon nanotube strength include [Treacy 96], [Yacobson 96], and [Srivastava 97a].

Space Elevator

[Issacs 66] and [Pearson 75] proposed a space elevator -- a cable extending from the Earth's surface into space with a center of mass at geosynchronous altitude. If such a system could be built, it should be mechanically stable and vehicles could ascend and descend along the cable at almost any reasonable speed using electric power (actually generating power on the way down). The first incredibly difficult problem with building a space elevator is strength of materials. Maximum stress is at geosynchronous altitude so the cable must be thickest there and taper exponentially as it approaches Earth. Any potential material may be characterized by the taper factor -- the ratio between the cable's radius at geosynchronous altitude and at the Earth's surface. For steel the taper factor is tens of thousands -- clearly impossible. For diamond, the taper factor is 21.9 [McKendree 95] including a safety factor. Diamond is, however, brittle. Carbon nanotubes have a strength in tension similar to diamond, but bundles of these nanometer-scale radius tubes shouldn't propagate cracks nearly as well as the diamond tetrahedral lattice. Thus, if the considerable problems of developing a molecular nanotechnology capable of making nearly perfect carbon nanotube systems approximately 70,000 kilometers long can be overcome, the first serious problem of a transportation system capable of truly large scale transfers of mass to orbit can be solved. The next immense problem with space elevators is safety -- how to avoid dropping thousands of kilometers of cable on Earth if the cable breaks. Active materials may help by monitoring and repairing small flaws in the cable and/or detecting a major failure and disassembling the cable into small elements.

Interplanetary transportation

[Drexler 92b] calculates that lightsails made of 20 nm aluminum in tension should achieve an outward acceleration of ~14 km/s per day at Earth orbit with no payload and minimal structural overhead. For comparison, the delta V from low Earth to geosynchronous orbit is 3.8 km/s. Lightsails generate thrust by reflecting sunlight. Tension is achieved by rotating the sail. The direction of thrust is normal to the sail and away from the Sun. By directing thrust along or against the velocity vector, orbits can be lowered or raised. This form of transportation requires no reaction mass and generates thrust continuously, although the instantaneous acceleration is small so sails cannot operate in an atmosphere and must be large for even moderate payloads.

Active Materials

Today, the smallest feature size in production systems is about 250 nanometers -- the smallest feature size in computer chips. Since atoms are an angstrom or so across and carbon nanotubes have a diameter as small as 0.7 nanometers, atomically precise molecular machines can be smaller than current MEMS devices by two to three orders of magnitude in each dimension, or six to nine orders of magnitude smaller in volume (and mass). For example, the size of the kinesin motor, which transports material in cells, is 12 nm. [Han 97a] computationally demonstrated that molecular gears fashioned from single-walled carbon nanotubes with benzyne teeth should operate well at 50-100 gigahertz. These gears are about two nanometers across. [Han 97c] computationally demonstrated cooling the gears with an inert atmosphere. [Srivastava 97c] simulated powering the gears using alternating electric fields generated by a single simulated laser. In this case, charges were added to opposite sides of the tube to form a dipole. For an examination of the state-of-the-art in small machines see the 1997 Conference on Biomolecular Motors and Nanomachines.

To make active materials, a material might be filled with nano-scale sensors, computers, and actuators so the material can probe its environment, compute a response, and act. Although this document is concerned with relatively simple artificial systems, living tissue may be thought of as an active material. Living tissue is filled with protein machines which gives living tissue properties (adaptability, growth, self-repair, etc.) unimaginable in conventional materials.

Swarms

Active materials can theoretically be made entirely of machines. These are sometimes called swarms since they consist of large numbers of identical simple machines that grasp and release each other and exchange power and information to achieve complex goals. Swarms change shape and exert force on their environment under software control. Although some physical prototypes have been built, at least one patent issued, and many simulations run, swarm potential capabilities are not well analyzed or understood. We briefly discuss some concepts here. For a summary of swarm concepts see [Toth-Fejel 96].

[Michael 94] proposes brick-shaped machines of various sizes that slide past each other to assume a variety of shapes. He has generated a large number of videos showing computer simulations of simple motions. Although his web site contains rather extravagant claims, this work has received a U. K. patent.

[Yim 95] built a small swarm with macroscopic (size in inches) components called polypod, built a simulator of polypod, and programmed it to move in various ways to study locomotion. There are two brick shaped components in polypod, one of which has two prismatic joints linked by a revolute joint. The second component is a cubic connector with no mechanical motion. Polypod is programmed by tables for each member of the swarm. Each member is programmed to move at various speeds in each degree of freedom for certain amounts of time. The swarm components are implicitly synchronized so there is no clock signal.

[Hall 96] proposes a swarm with 10 micron dodecahedral components each with 12 arms that can move in and out, rotate a little, and grab and release each other. This concept is called the "utility fog." [Hall 96] estimates that the utility fog would have a density of 0.2, tensile strength of 1000 psi in action and 100,000 psi in a passive mode, and have a maximum shear rate of 100 km/second/meter.

[Bishop 95] proposes a swarm consisting of 100 nanometer brick-shaped components that slide past each other to change shape.

[Globus 97] proposes a swarm with two kinds of components -- edges and nodes. The terms "node" and "edge" are chosen to correspond to those in graph theory. The roughly spherical nodes are capable of attaching to five edges (for a tetrahedral geometry with one free edge per node) and rotating each edge in pitch and yaw. The rod-like edges are capable of changing length, rotating around their long axis, and attaching/detaching to/from nodes. See figure.

Component design, power distribution and control software are significant challenges for swarm development. Consider that with 10 micron components a cubic meter of swarm would contain about 10^{15} devices, each with an internal computer communicating with its neighbors to accomplish a global task.

NASA Missions

NASA's mission is divided into five enterprises: Mission to Planet Earth, Aeronautics, Human Exploration and Development of Space, Space Science, and Space Technology. We will examine some potential nanotechnology applications in each area.

Mission to Planet Earth

EOS Data System

The Earth Observing System (EOS) will use satellites and other systems to gather data on the Earth's environment. The EOS data system will need to process and archive >terabyte per day for the indefinite future. Simply storing this quantity of data is a significant challenge -- each day's data would fill about 1,000 DVD disks. With projected write-once nanomemory densities of 10^{15} bytes/cm^2 [Bauschlicher 97a] a year's worth of EOS data can be stored on a small piece of diamond. With projected nanocomputer processing speeds of 10^{18} MIPS [Drexler 92a], a million calculations on each byte of one day's data would take one second on the desktop.

Smart Dust

Given a mature nanotechnology, it should be possible to build sensors in balloon-borne systems approximately the size of bacteria. With replication based manufacturing, these should be quite inexpensive. If the serious communication and control problems can be solved, one can imagine spreading billions of tiny lighter-than-air vehicles into the atmosphere to measure wind currents and atmospheric composition. A similar approach might be taken in the oceans -- note that the oceans are full of floating microscopic living organisms that can sense and react to their environment. Smart dust might sense the environment, note the location via a GPS-like system, and store that information until close enough to a data-collection point to transfer the data to the outside world.

Aeronautics and Space Transportation Technology

The strength of materials and computational capabilities previously discussed for space transportation should also allow much more advanced aircraft. Stronger, lighter materials can obviously make aircraft with greater lift and range. More powerful computers are invaluable in the design stage and of great utility in advanced avionics.

Active surfaces for aeronautic control

MEMS technology has been used to replace traditional large control structures on aircraft with large numbers of small MEMS controlled surfaces. This control system was used to operate a model airplane in a windtunnel. Nanotechnology should allow even finer control -- finer control than exhibited by birds, some of which can hover in a light breeze with very little wing motion. Nanotechnology should also enable extremely small aircraft.

Complex Shapes

A reasonably advanced nanotechnology should be able to make simple atomically precise materials under software control. If the control is at the atomic level, then the full range of shapes possible with a given material should be achievable. Aircraft construction requires complex shapes to accommodate aerodynamic requirements. With molecular nanotechnology, strong complex-shaped components might be manufactured by general purpose machines under software control.

Payload Handling

The aeronautics mission is responsible for launch vehicle development. Payload handling is an important function. Very efficient payload handling might be accomplished by a very advanced swarm. The sequence begins by placing each payload on a single large swarm located next to the shuttle orbiter. The swarm forms itself around the payloads and then moves them into the payload bay, arranging the payloads to optimize the center of gravity and other considerations. The swarm holds the payload in place during launch and may even damp out some launch vibrations. On orbit, satellites can be launched from the payload bay by having the swarm give them a gentle push. The swarm can then be left in orbit, perhaps at a space station, and used for orbital operations.

This scenario requires a very advanced swarm that can operate in an atmosphere and on orbit in a vacuum. Besides the many and obvious difficulties of developing a swarm for a single environment, this provides additional challenges. Note that a simpler swarm might be used for aircraft payload handling.

Vehicle Checkout

Aerospace vehicles often require complex checkout procedures to insure safety and reliability. This is particularly true of reusable launch vehicles. A very advanced swarm with some special purpose appendages might be placed on a vehicle. It might then spread out over the vehicle and into all crevices to examine the state of the vehicle in great detail.

Human Exploration and Development of Space

Nanotechnology-enabled Earth-to-orbit transportation has the greatest potential to revolutionize human access to space by dropping the current $10,000 per pound cost of launch, but this was discussed above. Other less dramatic technologies include:

High Strength and Reliability Materials

Space structures with a long design life (such as space station modules) need high-reliability materials that do not degrade. Active materials might help. The machines monitor structural integrity at the sub-micrometer scale. When a portion of the material becomes defective, it could be disassembled and then correctly reassembled. It should be noted that bone works somewhat along these lines. It is constantly being removed and added by specialized cells.

On Demand Spares and Tools

To effect timely repairs, space stations require a large store of spare parts and tools that are rarely used. A mature nanotechnology might create a "matter compiler," a machine that converts raw materials into a wide variety of products under software control. Contemporary examples of very limited matter compilers are numerically controlled machines and polypeptide sequencers. With a substantially more capable nanotechnology-based matter compiler, a space station crew could simply make spare parts and tools as needed. The programs could be stored on-board or on the ground. New tools invented on Earth could be transferred as software to the station for manufacture. Once used, unneeded tools and broken parts could be ionized in a solar furnace, transferred using controlled magnetic fields, and the constituent atoms stored for later manufacture into new products.

Waste Recycling

An advanced nanotechnology might be able to build filters that dynamically modify themselves to attract the contaminant molecules detected by the air and water quality sensors. Once attached to the filter, the filter could in principle move the offending molecules to a molecular laboratory for modifications to useful or at least inert products. A swarm might implement such an active filter if it was able to dynamically manufacture proteins that could bind contaminant molecules. The protein and bound contaminant might then be manipulated by the swarm for transportation.

With a sufficiently advanced nanotechnology it might even be possible to directly generate food by non-biological means. Then agriculture waste in a self-sufficient space colony could be converted directly to useful nutrition. Making this food attractive will be a major challenge.

Sleeping through RCS firings

Sleeping crew members in the shuttle experience considerable pain and sleep disruption when the reaction control system fires and they collide with the cabin walls. If crew members were connected to the walls by a swarm, the swarm could absorb most or all of the force before the crew member struck the wall. The swarm could then gradually return the crew member to center (without the oscillations associated with bungee cords) in preparation for the next firing.

Spacecraft Docking

For resupply, spacecraft docking is a frequent necessity in space station operations. When two spacecraft are within a few meters of each other, a swarm could extend from each, meet in the middle, and form a stable connection before gradually drawing the spacecraft together.

Zero and Partial G Astronaut Training

A swarm could support space-suited astronauts in simulated partial-g environments by holding them up appropriately. The swarm moves in response to the astronaut's motion providing the appropriate simulation of partial or 0 gravities. Tools and other objects are also manipulated by the swarm to simulate non-standard gravity.

Smart Space Suits

Active nanotechnology materials (see active materials) might enable construction of a skin-tight space suit covering the entire body except the head (which is in a more conventional helmet). The material senses the astronaut's motions and changes shape to accommodate it. This should eliminate or substantially reduce the limitations current systems place on astronaut range of motion.

Small Asteroid Retrieval

In situ resource utilization is undoubtedly necessary for large scale colonization of the solar system. Asteroids are particularly promising for orbital use since many are in near Earth orbits. Moving asteroids into low Earth orbit for utilization poses a safety problem should the asteroid get out of control and enter the atmosphere. Very small asteroids can cause significant destruction. The 1908 Tunguska explosion, which [Chyba 93) calculated to be a 60 meter diameter stony asteroid, leveled 2,200 km^2 of forest. [Hills 93] calculated that 4 meter diameter iron asteroids are near the threshold for ground damage. Both these calculations assumed high collision speeds. At a density of 7.7 g/cm^3 [Babadzhanov 93], a 3 meter diameter asteroid should have a mass of about 110 tons. [Rabinowitz 97] estimates that there are about one billion ten meter diameter near Earth asteroids and there should be far more smaller objects.

For colonization applications one would ideally provide the same radiation protection available on Earth. Each square meter on Earth is protected by about 10 tons of atmosphere. Therefore, structures orbiting below the van Allen belts would like 10 $tons/meter^2$ surface area shielding mass. This would dominate the mass requirements of any system and require one small asteroid for each 11 $meter^2$ of colony exterior surface area. A 10,000 person cylindrical space colony such as Lewis One [Globus 91] with a diameter of almost 500 meters and a length of nearly 2000 meters would require a minimum of about 90,000 retrieval missions to provide the shielding mass. The large number of missions required suggests that a fully automated, replicating nanotechnology may be essential to build large low Earth orbit colonies from small asteroids.

A nanotechnology swarm along with an atomically precise lightsail is a promising small asteroid retrieval system. Lightsail propulsion insures that no mass will be lost as reaction mass. The swarm can control the lightsail by shifting mass. When a target asteroid is found, the swarm spreads out over the surface to form a bag. The interface to the sail must be active to account for the rotation of the asteroid -- which is unlikely to have an axis-of-rotation in the proper direction to apply thrust for the return to Earth orbit. The active interface is simply swarm elements that transfer between each other to allow the sail to stay in the proper orientation. Of course, there are many other possibilities for nanotechnology based retrieval vehicles.

Extraterrestrial Materials Utilization

Extraterrestrial materials brought into orbit could be fed into a high-temperature solar furnace and partially ionized. Magnetic fields might then be used to separate the nuclei. These are fed in appropriate quantities to a matter-compiler to build the products desired.

Medical Applications

Several authors, including [Freitas 98] have speculated that a sufficiently advanced nanotechnology could examine and repair cells at the molecular level. Should this capability become available -- presumably driven by terrestrial applications -- the small size and advanced capabilities of such systems could be of great utility on long duration space flights and on self-sufficient colonies.

Terraforming

Self-replicating systems permit efforts of great scope to be pursued economically. Adjusting the environment on another planet to suit the tastes of humans is one such undertaking. Heating and cooling can be achieved by (among many other methods) using space-based mirrors. Chemical modifications of the planetary surface and atmosphere can be achieved in relatively short periods by the use of self-replicating systems that absorb sunlight and raw materials, and convert them into the desired products. Much as plants changed the environment of the earth to what we see today, so self-replicating molecular manufacturing systems might more rapidly convert the environments of other planets.

Suspended Animation

As interstellar trips might last many years, the ability to conserve supplies by maintaining some crew members in a suspended state would be useful. An extremely advanced nanotechnology might use molecular manipulations of each cell to provide (a) better methods of slowing or suspending the metabolic activity of crew members and (b) better methods of restoring metabolic activity to a normal state when the destination is reached.

Space Science

Space Telescopes

Molecular manufacturing should enable the creation of very precise mirrors. Unlike lightsail applications, telescope mirrors require a very precise and somewhat complicated shape. A swarm with special purpose appendages capable of bonding to the mirror might be able to achieve and maintain the desired shape.

Virtual Sample Return

A very advanced nanotechnology would be capable of imaging and then removing the surface atoms of an extra-terrestrial sample. By removing successive surface layers the location of each atom in the sample might be recorded, destroying the sample in the process. This data could then be sent to Earth. Besides requiring a very advanced nanotechnology, there is a more fundamental -- but not necessarily fatal -- problem: as the outside layer of atoms is removed the next layer may rearrange itself so the sample is not necessarily perfectly recorded.

Meteorological Data

As described earlier in the EOS section, smart dust could be distributed into the atmosphere of another planet to characterize it in great detail.

Space Technology

Solar Power

Low Earth orbit spacecraft generally depend on solar cells and batteries for power. According to [Drexler 92b]:

> For energy collection, molecular manufacturing can be used to make solar photovoltaic cells at least as efficient as those made in the laboratory today. Efficiencies can therefore be > 30%. In space applications, a reflective optical concentrator need consist of little more than a curved aluminum shell < 100 nanometers thick (photovoltaic cells operate with higher efficiency at high optical power densities). A metal fin with a thickness of 100 nanometers and a conduction path length of 100 microns can radiate thermal energy at a power density as high as 1000 W/m^2 with a temperature differential from base to tip of < 1 K.
>
> Accordingly, solar collectors can consist of arrays of photovoltaic cells several microns in thickness and diameter, each at the focus of a mirror of ~100 micron diameter, the back surface of which serves as a ~100 micron diameter radiator. If the mean thickness of this system is ~1 micron, the mass is ~10^{-3} kg/m^2 and the

power per unit mass, at Earth's distance from the Sun, where the solar constant is ~1.4 kW/m^2, is > 10^5 W/kg."

By comparison, the U.S. built Photovoltaic Panel Module solar cells currently used on the Mir Space Station and planned for use on the International Space Station generate about 118 W/kg.

Power Storage

Fuel Cells

A critical component in hydrogen/oxygen fuel cells is the PEM (Proton Exchange Membrane). This membrane must (a) permit the passage of protons while (b) blocking everything else. Present membranes do a rather poor job. One group at Ames is designing and computationally testing PEMs to study possible energy mechanisms in early life. While these studies are not meant to design optimal membranes for fuel cell use, the basic knowledge and approach may be of value. Another proposal is to design a diamond membrane a few nanometers thick with "proton pores." The pores might be lined with fluorine, oxygen and nitrogen to create a region with a high proton affinity. In addition, a positionally controlled platinum might be held at the mouth of the pore to verify that H_2 can be catalytically split into H+ and e-, and that the barrier for migration of the H+ into the pore is modest in size. Nanotechnology must provide precise control over the manufacturing process of the diamondoid PEM since the pores must be made very precisely.

Hydrogen Storage

Studies of H_2 absorption and packing in carbon nanotubes and nanoropes are in progress at NASA Ames and elsewhere. Nanotubes provide large pore sizes and nanoropes have different pore sizes depending on interstitial and other locations. [Dillon 97] estimated that the single walled nanotubes in their sample contained 5 to 10% by weight of H_2. The nanotubes were about 0.1 to 0.2% by weight of the total sample. Computational studies at Ames suggest that to store 7-10% H_2 in single walled nanotubes at room temperature the H_2s must be stored inside the tubes, not merely adsorbed on the walls [Srivastava 97d]. This work suggests that carbon nanotubes might be developed into an excellent H_2 storage medium within 3-5 years.

Oxygen Storage

Calculations with oxygen [Merkle 94] suggest that a diamondoid sphere ~0.1 microns in diameter should easily hold oxygen at ~1,000 atmospheres. While higher pressures are feasible, they offer declining returns. At higher pressures, the pressure-volume relationship becomes severely non-linear and the density approaches a limiting value. Other gases might also be stored if diamondoid spheres can be built, but the analysis has not been done.

Fly Wheels

High strength light-weight materials will allow greater efficiency of energy storage as angular momentum.

Nano Electromechanical Sensors

Many kinds of ultraminiature electromechanical devices have utility on a miniaturized space craft. It has been shown that manipulating carbon nanotubes changes their electrical properties [Srivastava 97b]. This might be exploited to build nanometer scale strain devices. This may be achievable within 3-5 years, and simulations along these lines are in progress.

Similar results have been achieved experimentally with C_{60} [Joachim 97]. The electrical properties of a C_{60} molecule were changed by applying pressure to the molecule with an SPM tip.

Miniature Spacecraft

Smaller, lighter spacecraft are cheaper to launch (current costs are about $10,000/lb) and generally cheaper to build. Diamondoid structural materials can radically reduce structural mass, miniaturized electronics can shrink the avionics and reduce power consumption, and atomically precise materials and components should shrink most other subsystems.

Thermal Protection

Thermal protection is crucial for atmospheric reentry and other tasks. The carbon nanotubes under investigation at NASA Ames and elsewhere may play a significant role. Most production processes for carbon nanotubes create a tangled mat of nanotubes that has a very low mass-to-volume ratio. Like graphite, the tubes should withstand high temperatures but the tangled mat should prevent them from ablating. This may lead to high temperature applications.

Conclusion

Many of the applications discussed here are speculative to say the least. However, they do not appear to violate the laws of physics. Something similar to these applications at these performance levels should be feasible if we can gain complete control of the three-dimensional structure of materials, processes and devices at the atomic scale.

How to gain such control is a major, unresolved issue. However, it is clear that computation will play a major role regardless of which approach -- positional control with replication, self-assembly, or some other means -- is ultimately successful. Computation has already played a major role in many advances in chemistry, SPM manipulation, and biochemistry. As we design and fabricate more complex atomically precise structures, modeling and computer aided design will inevitably play a critical role. Not only is computation critical to all paths to nanotechnology, but for the most part the same or similar computational chemistry software and expertise supports all roads to molecular nanotechnology. Thus, even if NASA's computational molecular nanotechnology efforts should pursue an unproductive path, the expertise and capabilities can be quickly refocused on more promising avenues as they become apparent.

As nanotechnology progresses we may expect applications to become feasible at a slowly increasing rate. However, if and when a general purpose programmable assembler/replicator can be built and operated, we may expect an explosion of applications. From this point, building new devices will become a matter of developing the software to instruct the assembler/replicators. Development of a practical swarm is another potential turning point. Once an operational swarm that can grow and divide has been built, a large number of applications become software projects. It is also important to note that the software for swarms and assembler/replicators can be developed using simulators -- even before operational devices are available.

Nanotechnology advocates and detractors are often preoccupied with the question "When?" There are three interrelated answers to this question (see also [Merkle 97] and [Drexler 91]):

1. Nobody knows. There are far too many variables and unknowns. Beware of those who have excessive confidence in any date.
2. The time-to-nanotechnology will be measured in decades, not years. While a few applications will become feasible in the next few years, programmable assembler/replicators and swarms will be extremely difficult to develop.

3. The time-to-nanotechnology is very sensitive to the level of effort expended. Resources allocated to developing nanotechnology are likely to be richly rewarded, particularly in the long term.

Acknowledgments

We would like to thank Steve Zornetzer, NASA Ames Research Center, for asking us to look into molecular nanotechnology applications to NASA missions. Special thanks to Glenn Deardorff and Chris Henze for reviewing the manuscript.

References

[Avouris 96] Ph. Avouris, R. E. Walkup, A. R. Rossi, H. C. Akpati, P. Nordlander, P.-C. Shen, G. G. Ablen and J. W. Wyding, "Breaking Individual Chemical Bonds via STM-Induced Exitations," *Surface Science*, 1 August 1996, V363 N1-3:368-377.

[Babadzhanov 1993] Pulat B. Babadzhanov, "Density of meteoroids and their mass influx on the Earth,"*Asteroids, Comets, Meteors 1993, Proceedings of the 160th symposium of the International Astronomical Union,* Belgirate, Italy, 14-18 June 1993, A. Milani, M. Di Martino and A. Cellino, editors, pages 45-54.

[Bauschlicher 97a] Charles W.Bauschlicher Jr., Alessandra Ricca and Ralph Merkle, "Chemical storage of data," *Nanotechnology*, volume 8, number 1, March 1997 pages 1-5.

[Bauschlicher 97b] Charles. W. Bauschlicher and M. Rosi, "Differentiating between hydrogen and fluorine on a diamond surface", submitted to Theor. Chem. Acta.

[Bauschlicher 97c] Charles. W. Bauschlicher and M. Rosi, unpublished.

[Bishop 95] Forrest Bishop, "The Construction and Utilization of Space Filling Polyhedra for Active Mesostructures," WWW page.

[Bumm 96] L. A. Bumm, J. J. Arnold, M. T. Cygan, T. D. Dunbar, T. P. Burgin, L. Jones II, D. L. Allara, James M. Tour, P. S. Weiss, "Are Single Molecular Wires Conducting?" *Science*, volume 271, 22 March 1996, pages 1705-1707.

[Chico 96] L. Chico, Vincent H. Crespi, Lorin X. Benedict, Steven G. Louie and Marvin L. Cohen, "Pure Carbon Nanoscale Devices: Nanotube Heterojunctions," *Physical Review Letters*, volume 76, number 6, 5 February 1996, pp. 971-974.

[Chyba 93] Christopher F. Chyba, Paul J. Thomas, and Kevin J. Zahnle, "The 1908 Tunguka explosion: atmospheric disruption of a stony asteroid," *Nature* volume 361, 7 January 1993, pages 40-44.

[Dai 96] H. Dai, J. H. Hafner, A. G. Rinzler, D. T. Colbert and R. E. Smalley, "Nanotubes as Nanoprobes in Scanning Probe Microscopy," *Nature* 384, pages 147-151, (1996).

[Dillon 97] A. C. Dillon, K. M. Jones, T. A. Bekkedahl, C. H. Kiang, D. S. Bethune, M. J. Heben, "Storage of hydrogen in single-walled carbon nanotubes," *Nature*, 27 March 1997, volume 386, N6623:377-379.

[Dresselhaus 95] M. S. Dresselhaus, G. Dresselhaus and P. C. Eklund, *Science of Fullerenes and Carbon Nanotubes*, Academic Press (1995).

[Drexler 91] K. Eric Drexler, Chris Peterson, and Gayle Pergami, *Unbounding the Future*, William Morrow and Company, Inc., (1991).

[Drexler 92a] K. Eric Drexler, *Nanosystems: Molecular Machinery, Manufacturing, and Computation*, John Wiley & Sons, Inc. (1992).

[Drexler 92b] K. Eric Drexler, *Journal of the British Interplanetary Society*, volume 45, number 10, pages 401-405 (1992).

[Freitas 98] Robert A. Freitas Jr., *Nanomedicine, Volume I: Basic Capabilities* , Landes Bioscience, Georgetown TX, 1998.

[Globus 91] Al Globus, "The Design and Visualization of a Space Biosphere," *10th Biennial Space Studies Institute/Princeton University Conference on Space Manufacturing*, Princeton University, May 15-18, 1991.

[Globus 97], Al Globus, Charles Bauschlicher, Jie Han, Richard Jaffe, Creon Levit, Deepak Srivastava, "Machine Phase Fullerene Nanotechnology," *Nanotechnology*, 9, pp. 1-8 (1998).

[Goldhaber-Gordon 97] D. J. Goldhaber-Gordon, M. S. Montemerlo, J. C. Love, G. J. Opiteck, and J. C. Ellenbogen, *Proceedings of the IEEE*, April 1997, V85 N4:521-540.

[Hall 96] J. Storrs Hall, "Utility Fog: The Stuff that Dreams are Made Of," *Nanotechnology: Molecular Speculations on Global Abundance,* B. C. Crandall, editor, MIT Press, Cambridge, Massachusetts, 1996; also in "Utility Fog," *Extropy*, 3rd (Part 1) and 4th quarter (Part 2), 1994. See WWW page Utility Fog: The Stuff that Dreams are Made Of.

[Han 97a] Jie Han, Al Globus, Richard Jaffe and Glenn Deardorff, "Molecular Dynamics Simulation of Carbon Nanotube Based Gears," *Nanotechnology*, volume 8, number 3, 3 September 1997, pages 95-102.

[Han 97b] Jie Han, M. P. Anantram, and Richard Jaffe, "Design and Study of Carbon Nanotube Electronic Devices," The Fifth Foresight Conference on Molecular Nanotechnology, 5-8 November, 1997, Palo Alto, CA.

[Han 97c] Jie Han, Al Globus, and Richard Jaffe, "The Molecular Dynamics of Carbon Nanotube Gears in He and Ne Atomspheres," The Fifth Foresight Conference on Molecular Nanotechnology, 5-8 November, 1997; Palo Alto, CA.

[Hills 93] Jack G. Hills and M. Patrick Goda, "The fragmentation of small asteroids in the atmosphere," *The Astronomical Journal,* March 1993, volume 105, number 3, pages 1114-1144.

[Iijima 91] Sumio Iijima, "Helical microtubules of graphitic carbon," *Nature*, 7 November 1991, volume 354, N6348:56-58.

[Issacs 66] John D. Issacs, Allyn C. Vine, Hugh Bradner and George E. Bachus, "Satellite Elongation into a True 'Sky-Hook'," *Science*, volume 151, 11 February 1966, pages 682-683.

[Joachim 97] C. Joachim and J. Gimzewski, "An Electromechanical Amplifier Using a Single Molecule," *Chemical Physics Letters*, volume 265, pages 353-357, 1997.

[McKendree 95] Tom McKendree, "Implications of Molecular Nanotechnology: Technical Performance Parameters on Previously Defined Space System Architectures," *The Fourth Foresight Conference on Molecular Nanotechnology*, Palo Alto, CA. (November 1995).

[Menon 97a] M. Menon, D. Srivastava and S. Saini, "Carbon Nanotube Junctions as Building Blocks for Nanoscale Electronic Devices," *Semiconductor Device Modeling Workshop at NASA Ames Research Center*, August (1997).

[Menon 97b] M. Menon and D. Srivastava, "Carbon Nanotube T-junctions: Nanoscale Metal-Semiconductor-Metal Contact Devices," submitted to *Phys. Rev. Lett.*, (1997).

[Merkle 94] Ralph C. Merkle, "Nanotechnology and Medicine," *Advances in Anti-Aging Medicine,* Vol. I, edited by Dr. Ronald M. Klatz, Liebert Press, 1996, pages 277-286.

[Merkle 96] Ralph C. Merkle and K. Eric Drexler, "Helical Logic," *Nanotechnology* (1996) volume 7 pages 325-339.

[Merkle 97] Ralph C. Merkle, "How long will it take to develop nanotechnology?" WWW page.

[Michael 94] Joseph Michael, UK Patent #94004227.2.

[Moore 75] Gordon Moore, "Progress in digital integrated circuits," *1975 International Electron Devices Meeting*, page 11. See the figure: approximate component count for complex integrated circuits vs. year of introduction and the following figures from *Miniaturization of electronics and its limits*, by R. W. Keyes, IBM Journal of Research and Development, Volume 32, Number 1, January 1988.

- Number of atoms used to store a bit in discrete magnetic entities and in file technologies.
- The decreasing number of dopant impurities in the base of bipolar transistors for logic.
- The decreasing energy dissipated per logic operation.

[Pearson 75] Jerome Pearson, *Acta Astronautica* **2** pages 785-799 (1995).

[Rabinowitz 97] David L. Rabinowitz, "Are Main-Belt Asteroids a Sufficient Source for the Earth-Approaching Asteroids? Part II. Predicted vs. Observed Size Distributions," *Icarus* 1997 May, V127 N1:33-54.

[Smith 97] Steven. S. Smith, Luming M. Niu, David J. Baker, John A. Wendel, Susan E. Kane, and Darrin S. Joy, "Nucleoprotein-based nanoscale assembly," *Proceedings of the National Academy of Sciences of the United States of America,* March 18 1997, V94 N6:2162-2167.

[Srivastava 97a] Deepak Srivastava and Steve T. Barnard, "Molecular Dynamics Simulation of Large-Scale Carbon Nanotubes on a Shared Memory Architecture," *SuperComputing 97* (1997).

[Srivastava 97b] Deepak Srivastava, Steve T. Barnard, S. Saini and M. Menon, "Carbon Nanotubes: Nanoscale Electromechanical Sensors", *2nd NASA Semiconductor Device Modeling Workshop at NASA Ames Research Center*, August 1997.

[Srivastava 97c] Deepak Srivastava, "Molecular Dynamics Simulations of Laser Powered Carbon Nanotube Gears," submitted to *Nanotechnology*.

[Srivastava 97d] Deepak Srivastava, "H_2 packing in Single Wall Carbon Nanotubes and Ropes by Molecular Dynamics Simulations," unpublished (1997).

[Taylor 93] R. Taylor and D. R. M. Walton, "The Chemistry of Fullerenes," *Nature*, volume 363, N6431, 24 June 1993, pages 685-693.

[Thummel 97] H. T. Thummel and C. W. Bauschlicher, "On the reaction of FNO_2 with CH_3, t-butyl, and $C_{13}H_{21}$," *J. Phys. Chem.*, 101, 1188 (1997).

[Toth-Fejel 96] Tihamer Toth-Fejel, "LEGO(TM)s to the Stars: Active MesoStructures, Kinetic Cellular Automata, and Parallel Nanomachines for Space Applications," *The Assembler,* Volume 4, Number 3, Third Quarter, 1996

[Tour 96] James M. Tour, "Conjugated Macromolecules of Precise Length and Constitution. Organic Synthesis for the Construction of Nanoarchitectures," *Chemical Review*, January-February 1996, volume 96, pages 537-553.

[Tour 97] James M. Tour, Masatoshi Kozaki and Jorge M. Seminario, "Molecular Scale Electronics: Synthetic and Computational Approaches To Nanoscale Digital Computing," unpublished 1997.

[Treacy 96] M. M. J. Treacy, T. W. Ebbesen and J. M. Gibson, "Exceptionally High Young's Modulus Observed for Individual Carbon Nanotubes," *Nature* 381, 678 (1996).

[Wowk 96] Bryan Wowk, "Phased Array Optics," *Nanotechnology: Molecular Speculations on Global Abundance,* B. C. Crandall, editor, MIT Press, Cambridge, Massachusetts, 1996.

[Wu 96] Ruilan Wu, Jeffry S. Schumm, Darren L. Pearson, and James M. Tour, "Convergent Synthetic Routes to Orthogonally Fused Conjugated Oligomers Directed towards Molecular Scale Electronic Device Applications," *Journal of Organic Chemistry*, volume 61, number 20, pages 6906-6921.

[Yacobson 96] Boris I. Yacobson, C. J. Brabec and J. Bernholc, "Nanomechanics of Carbon Tubes - Instabilities Beyond Linear Response," *Physical Review Letters*, 1 April 1996, V76 N14:2511-2514.

[Yim 95] Mark Yim, "Locomotion With A Unit-Modular Reconfigurable Robot," Stanford University Technical Report STAN-CS-TR-95-1536.

Web work: Al Globus, Responsible Official: Creon Levit.