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Nanorobots for Mars EVA Repair

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ABSTRACT

Current trends in technology indicate that nanometer-scale devices will be feasible within two decades. It is likely that NASA will attempt a manned Mars mission within the next few decades. Manned Mars activities will be relatively labor-intensive, presenting significant risk of damage to the Marssuit. We have investigated two possible architectures for nanotechnology applied to the problem of damage during Mars surface activity.

Nanorobots can be used to actively repair damaged suit materials while an astronaut is in the field, precluding the need to return immediately to a pressurized area. Assembler nanorobots reproduce both themselves and the more specialized Marssuit Repair Nanorobots (MRN). MRN nanorobots operate as space-filling polyhedra to repair damage to a Marssuit. Both operate with reversible mechanical logic, though only assemblers utilize chemical data storage.

INTRODUCTION

Humans will be sent to Mars to accomplish objectives that robotic missions cannot. "Surface exploration is the key to the mission," requiring long periods of Mars surface activity.[1] Astronauts will be performing strenuous activities to meet many objectives, such as digging for samples, climbing rocks, and hiking long distances. This will continue for 18 to 20 months, 600 days nominal, under the NASA Mars Reference Mission.[1] Wear and tear on the suits will be a problem as never before, due to a combination of strenuous activities, damaging terrain, and duration of use. The protection of the astronaut in the field depends entirely on his Marssuit. Because the probability of Marssuit damage in the field is not negligible, we must develop possible solutions to this problem.

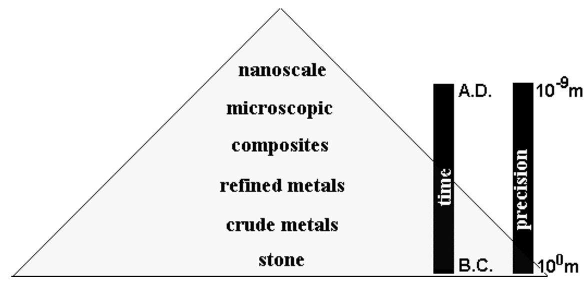


Figure 1: Human Technical Advancement -- *As history has progressed from the Stone Age to the 21st Century, the level of precision that humans have been able to achieve has increased with the complexity of their tools and materials.*

Since the Stone Age, man has gained increasing facility with materials. Once man had mastered stonework, he was able to begin the refinement of ores into increasingly pure substances. Relatively recently, a surge in advancement resulted from the Bessemer Process for making steel. Twenty years ago, an engineer's proverbial bread and butter was aluminum and steel. Today, high strength composites such as carbon fiber are playing an increasing role in advanced aerospace applications. The trend is apparent. As we gain facility with the manipulation of matter, what was yesterday's advancement becomes today's staple tool. Eventually we will achieve cheap, thorough, and inexpensive control over the structure of matter. This means molecular manufacturing – building objects up from the individual atoms and molecules. Initially this will result in materials for use in conventional applications, such as high-strength diamond fibers and buckminster fullerene 'buckytubes.' As our experience at the nanometer scale increases, we will move into nanorobotics. (Figure 1)

PROBLEM STATEMENTS

Failure modes can be classified into two categories:

1. Tears

The tearing failure mode is characterized by the separation of layers by a lengthwise scrape or cut.

Minimal loss of suit material is associated with this failure mode. A tear might be caused by laceration with a sharp implement such as a surgical blade, stretching suit material significantly past its elastic range, or by scraping on a sharp rock. Overstretching should not be a consideration for a well designed suit.

2. Punctures

A puncture is characterized by a large hole. Significant damage is inflicted on the suit in the immediate area of the puncture. It is unlikely that naturally occurring Martian rocks will be able to puncture a Marssuit during routine surface activities. A projectile, perhaps accidentally 'launched' from some machinery, might attain sufficient velocity to puncture a suit. More likely, punctures will be self-inflicted by geologic field tools such as picks and chisels. The damage area may be tattered, with lower structural integrity in the surrounding material due to deformation caused by foreign object entry.

3. Abrasion

Abrasion will be an ever-present detriment to the suit. A comparison is made to jeans which while tough when new, gradually wear thin at the knees or seat area. Unlike the catastrophic failure modes already mentioned, abrasion is a gradual degradation that can eventually lead to failure. Furthermore, failure due to abrasion can be prevented. The proposed architecture must address the problem of abrasion.

It is of further utility that we define two stages of failure. Primary failure, which can be likened to medical cases in which death is a possibility, is damage that extends to the pressure-retaining layer. Gas loss is the chief concern in primary failure. Of less danger, but commanding immediate attention nonetheless, are secondary failures. These failures define the class of damages that do not penetrate the pressure-retaining layer. Gas loss is not significant, as the pressure bladder remains intact.

Biological containment will be virtually impossible for a manned mission, due to nonzero suit leakage and other factors. Thus biological contamination will not be viewed as a problem, but rather as a consequence of sending humans to Mars.

REQUIREMENTS

The repair solution must either allow the astronaut to continue working, or provide enough time to return to the pressurized habitat safely. The astronaut must be alerted of any breaches that occur, so that a rational decision can be made early on.

Any system that is sent to Mars must be able to function in the Martian environment. A successful nanoscale solution must withstand the detriment of thermal noise and maintain positional accuracy in the range of Martian temperatures. Dust is also a primary concern for mechanical systems.

In order for nanorobots to be economically feasible, they must incorporate some level of self-replication. The inherent danger in self-replicating systems is the possibility of replication without bound.[2] So, it is necessary to precisely control any replication that occurs.

To minimize the time until such a repair system is practical, it is necessary to initially design a system utilizing a comparatively low level of nanoscale technologies. However, as experimentation increases our knowledge and manufacturing capabilities, this may no longer be necessary.

RESULTS

Harsh Martian conditions pose many problems to conventional mechanical systems. Dust can clog bearings and mechanisms as well as cause wear and tear. Average Martian temperatures of 223K at the equator and 143K at the poles can pose problems for many systems, affecting fluid viscosity and decreasing the elasticity of materials.[3] For molecular-scale systems, however, decreasing temperature merely reduces thermal noise, or the positional uncertainty that is caused by molecular vibration. The equipartition theorem gives each energy term in a system at thermal equilibrium a mean value of $\frac{1}{2}k_B T$ where k_B is the Boltzmann constant and T is the absolute temperature.[4] The maximum positional variance squared is thus $k_B T/k$ where k is the stiffness (spring constant) in N/m.[5] The proportionality of positional variance to temperature indicates that a lower temperature increases the accuracy of nanometer-scale mechanical devices. The decreased temperature relative to Earth will serve to increase the accuracy of any molecular positional device.

SINGLE WALL CARBON NANOTUBES

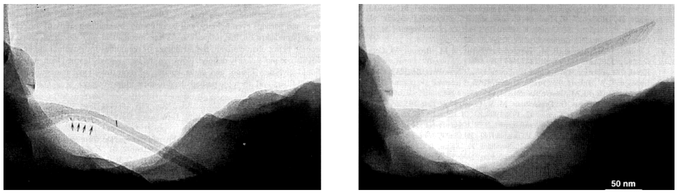


Figure 3: Elastic Properties of Nanotubes – *Single wall carbon nanotubes have been shown to possess extraordinary elasticity. Buckling effects are observed (arrows, left) under applied load, but there is no permanent deformation.[6]*

Different configurations of carbon yield materials of unique characteristics. Diamond, for example has a cubic lattice configuration and is the hardest material known to man. Carbon fiber is a staple material in the aerospace industry, due to its high strength/weight ratio. Buckminster fullerenes, or single wall carbon nanotubes (SWNT), are a class of diamondoid structures that are of particular interest. Carbon nanotubes have been experimentally tested to have an average Young's modulus of circa 2 TPa.[6] By comparison, the Young's modulus for carbon fiber is 0.8 TPa for relatively high purity samples.[7] In considering the energetics of SWNT deformation, it is useful to examine the energy required to bend a tube. Tibbetts' equation for strain energy is of the form:[8]

$$\frac{E_{bend}}{N} = \frac{Ea^3}{24}\frac{\Omega}{R^2} = \frac{C}{R^2}$$

where *E* is the elastic modulus, *R* is the radius of curvature, *L* is the length of the cylinder, and *a* is a representative thickness of the order of the graphite interplanar spacing (3.35 Å). The total number of carbon atoms is given by $N=2\pi RL/\Omega$ where Ω is the area per carbon atom.

The results of this theoretical model indicate that the energetics of deformation for SWNT nanotubes favor extreme elasticity. They are able withstand significant stresses without permanent deformation. These predictions have been confirmed through experimental observation as seen in Figure 3.

The properties of carbon nanotubes indicate that they may be useful in strong composites. A chief determining factor of fibrous composite stiffness is the axial ratio (length/thickness) of the constituent fibers. Manufacturers, however, desire shorter fibers for use in low-cost injection molding processes. Because of their inherently small size, carbon nanotubes can achieve exceptional axial ratios. Typical SWNT diameters are on the order of 1-2 nm (10-20 atomic diameters), with experimentally achieved lengths of thousands times the diameter.[9] Even in the case of an axial ratio of 1000, it would merely mean dealing with fibers on the order of 10^{-6} m. Typical short fiber glass or carbon fiber axial ratios are around 10 (length/thickness) with micron diameters. The uniform linear crystalline structure of SWNT nanotubes (Figure 4) indicates that unlimited length nanotubes are theoretically possible. If 'spool length' nanotubes were achieved, the application of SWNT fibers would be extended into the realm of continuous fiber composites. Graphitic carbon and glass are the most commonly used continuous fiber materials. Interwoven continuous fiber nanotube composites would possess desirable characteristics, such as extremely high modulus and the ability to withstand large loads in the direction of fiber orientation.

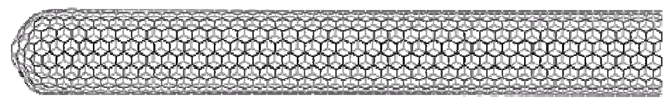


Figure 4: Buckytube Structure – *Single wall carbon nanotubes are typically 1-2 nm in diameter, and can theoretically be any length.[9]*

For the technological level of the proposed architecture, active abrasion repair is not incorporated. Instead, we rely on advanced suit materials such as interwoven nanotube fabrics. Theoretical models done by Yakobson and Smalley indicate nanotube fabrics will have the desirable property of inhibiting stress singularity propagation.[10] This is just a manifestation of the familiar property of many matrix composites: crack deflection along the fiber due to low interfacial strength. In the case of a nanotube fiber bundle, the interfacial bonding is due to the van der Waals force – the same characteristic that gives graphite its lubricity. The crack deflection is a key feature we seek in preventing abrasions from growing into more serious damage. A preventative measure might be to incorporate replaceable pads into high-wear areas of the suit. These high wear areas can be determined by simulation, or by observing real geologists in the field.

Carbon nanotube materials have the potential to replace contemporary composites in aerospace applications. High tensile strength nanotube fabrics will be stronger than Kevlar, and should prevent Marssuit punctures in all but the most strenuous conditions. Stiff nanotube matrix composites should be much stronger than current carbon fiber composites, while retaining the toughening mechanisms of crack deflection and fiber pullout. Marssuits will undoubtedly use the most advanced materials, and so the focus must shift to when Marssuits fail.

NANOROBOTICS

A robot is a combination of a computer and a constructor, in the most general case a Universal Computer (something that can calculate anything computable) combined with a Universal Constructor (something that can build anything that can be built).[11, 12] This combination could, in Von Neumann's theory, reproduce anything, including itself. When one shrinks this robot to a nanometer scale, it becomes both economical and practical to manufacture nanorobots to repair a Marssuit.

This architecture contains two distinct types of robots: assemblers and MRN nanorobots. It is not necessary to have designed and implemented Von Neumann's Universal Constructor to have practical assemblers. These assembler nanorobots need only the capability to reproduce themselves and to manufacture MRN nanorobots. Assembly takes place in a specially constructed tank, which remains in the habitat, manufacturing MRN nanorobots and assemblers whenever needed. MRN nanorobots are removed from the solution and added to the suit to begin their work. Though based on the same technology, these different robots have significant differences in design and capabilities due to their different roles.

The system of assembler nanorobots utilizes a broadcast architecture (Figure 5), both to decrease complexity and increase safety.[5] Each “molecular constructor,” or assembler, has a very limited onboard computer, limited mostly to interpreting and applying instructions broadcast from a macroscopic computer. It is far more practical to perform the complex calculations necessary to build nanorobots of many precisely placed molecules in a macroscopic computer. To move this task to the assembler would require far greater processing power and storage capability than will be practical for some time to come. This architecture also enforces the most basic possible safety precaution: protection against undue replication. As each assembler has only enough capability to decode and carry out the instructions transmitted to it, it cannot start replicating without bound. This simple precaution can prevent the “extraordinary accident” of runaway replication.[13]

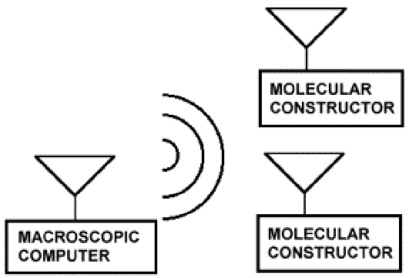


Figure 5: Broadcast Architecture – *In a broadcast architecture, many molecular constructors are under the complete control of a single macroscopic computer.[5]*

Instructions can be transmitted in a variety of ways, but the simplest and most practical for our purposes utilizes the liquid environment of the assembly tank. The macroscopic computer can transmit information acoustically.[1] Each assembler can be equipped with a pressure sensor and the rise and fall in pressure can be interpreted as instructions. Though chemical signals, like those used in biological organisms, are possible, the slowness and sensor complexity required for this scheme is prohibitive.

This liquid environment not only allows communication, but practical dissemination of needed molecules to the assemblers. Energy and raw materials are suspended in the “feedstock” liquid.[2] Fuels can be added for energy, and easily manufactured ‘parts’ reduce the complication of assembly. These ‘parts’ are actually molecules that can be easily linked together by the assembler, and thus are ideal building materials. Wastes can be disposed of easily into the feedstock. By designing the assemblers to rely on this feedstock, we add another measure of safety to our design.[14]

Assembler robots are far more flexible in their capabilities than their MRN nanorobot counterparts. MRN nanorobots are specialized robots, made to find damage in the suit, recognize it, and repair it. Assemblers have a manipulator that can be turned to a wide variety of tasks, making the extreme safety precautions a necessary part of their design. The MRN nanorobots have only one task, and so its instructions can be programmed into the design and checked before they are deployed. Should a MRN nanorobot’s logic be damaged, it becomes as useless and harmless due to its limited capabilities. This is an acceptable outcome, as it cannot harm the astronaut. It is impractical to attempt to communicate with the nanorobots in any case, as they lack a suitable medium for signal transmission.

In a liquid medium, pressure or chemical signals can be sent to a large number of nanorobots at once. However, sending these sorts of messages through a mixture of gas and other nanorobots is not practical. The movement of the astronaut will destroy pressure signals. Chemicals have no medium to travel though. Extremely weak electrical signals could be passed through a thin layer bonded to the suit’s inner layer. However, MRN nanorobots that are not in contact with this layer cannot receive the signals. Signals can be passed from robot to robot using any of these means during contact. Due to the extreme complexity of controlling this sort of a distributed network and the essential unpredictability of signal transmission, this proposed architecture does not incorporate these capabilities. The system will function without it, and requires a lower level of technology, decreasing the time needed before it is possible.

We shall take a strategic approach to the design requirements of Marssuit Repair Nanorobots. When the suit is damaged, the nanorobots should converge upon the affected area and begin repair, much like our own biological repair system. The method in which they 'attack' the damage must be fast and efficient. Because of the time constraints, a molecular level reconstruction of the suit material is unfeasible. Temporary repair solutions are attractive if they are fast. The logical nanorobotic approach is to utilize fast-moving nanorobots to fill up the breach. This can be accomplished with nanorobots in the form of space-filling polyhedra (SFP). (Figure 6) SFP nanorobots quickly seal breaches by interlocking with one another in successive waves until the damage is sealed.

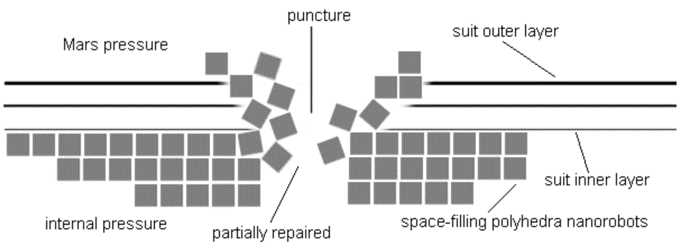


Figure 6: Space-Filling Polyhedral Nanorobots – *Space-filling polyhedral nanorobots rapidly converge upon damaged areas and seal them*

Virtually every robot ever constructed has been made up of four common components.[15] These general design principles carry over as well into the molecular scale, and provide general guidelines for organization. A manipulator is "a collection of mechanical linkages connected by joints to form an open-loop kinematic chain" used for any manipulation or movement by the robot.[15] Sensors convey information about the status of the manipulator or any number of outside conditions. The controller is the 'brain' of the robot, sequencing and interpreting data from the sensors to control the manipulator. The power-conversion unit provides energy to the system.

MANIPULATOR

In order to operate effectively at the atomic scale, scientists require methods for manipulating the atomic world. Chemists have been operating at the atomic scale for centuries, but deliberate placement of molecules to specific sites has only been achieved recently. Today's method of atomic manipulation requires extensive laboratory equipment such as atomic force microscopes (AFM). This is laborious, and economic production of large quantities of tailored atomic constructions is unfeasible by this method. If we are to achieve efficient control of atomic level constructions, we must have 'hands' that are equivalent in scale.

Intrinsic to any successful manipulation tool is high positional accuracy. Nanometer positional devices will necessarily be stiff in order to combat the detrimental effects of thermal noise. They must also achieve a required positional range. For atomic construction, a manipulator must have six degrees of freedom. Merkle's analysis of six degrees of freedom positional devices gives a reasonable analysis of possible manipulator configurations.[16] His conclusions indicate that serial devices (multiple joint arms) are inferior to the parallel devices that utilize extending struts for positional determination. Among parallel devices, the Stewart platform (Figure 7) is of interest because of its simplicity.

The Stewart platform consists of a tool-holding mechanism with a triangular base and six movable struts. For nanorobotic purposes, the tip of the Stewart platform serves as a versatile nest site where variable-affinity molecular 'tools' can be affixed. An excellent aspect of the Stewart platform is that the struts need only support tension and compressive forces, as the bending moments are negligible due to the constraints of the design.

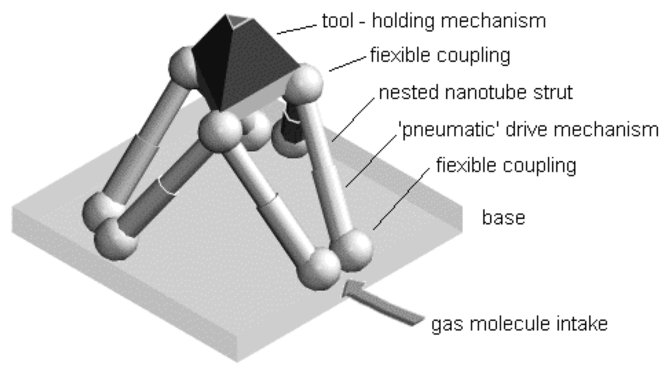


Figure 7: The Stewart Platform – *The Stewart platform has six 100 nm length struts, which provide six degrees of positional freedom to the manipulator tip.*

If Stewart platforms are to be used on Mars, their properties must be examined. To specify the minimum diameter of the struts, a numerical exercise is useful.

Stretching stiffness is given by:

$$k_{stretch} = \pi r^2 E / L$$

where E is Young's modulus (2×10^{12} Pascals for SWNT nanotubes), L is the length of the strut in meters, and $k_{stretch}$ is the equivalent spring constant, k. By equating spring energy and thermodynamic energy for a small displacement along a rod axis, it is found that

$$\text{Positional variance} = \sigma^2 = k_B T / k \qquad \textbf{(4.1)}$$

where σ is the mean displacement. By substitution,

$$\text{Positional variance} = \sigma^2 = k_B TL / (\pi r^2 E) \quad \textbf{(4.2)}$$

or, in terms of the minimum diameter to meet positional requirements,

$$\text{Diameter} = 2r = 2\,[k_B TL / (\pi \sigma^2 E)]^{1/2} \quad \textbf{(4.3)}$$

The numerical values used are:

$L = 10^{-7}$ m (100 nm)

Positional variance (choose 1/10 of an atomic diameter):

$\sigma^2 = (0.1\ \text{Å})^2 = 10^{-22}$ m

$E = 2\text{x}10^{12}$ Pa (Young's modulus for carbon nanotubes)

$k_B T = 3\text{x}10^{-21}$ J (using Mars' mean equatorial temperature, 223K)

By substitution into Equation 4.3, the minimum strut diameter is found to be 1.4 nm. Single wall carbon nanotubes are precisely applicable as struts. In fact, SWNT nanotubes are the only viable molecular structure that has all the properties we seek. Macroscopic actuator bodies are usually constructed from aluminum or steel. For the same reasons (simplicity and strength), the 'monoelemental polymer' structure of SWNT nanotubes make them a good choice. Because of carbon nanotubes' hollow cylindrical nature and high modulus, they are uniquely suited to acting as linear actuators. Nested nanotube actuators can be driven by pressure differences. (Figure 8) By varying the internal pressure with feedstock molecules, the nanotube strut can be made to extend or retract.

The effective seal of properly nested carbon nanotubes 3.35 Å due to the van der Waals radii between the constituent carbon atoms in the nanotubes. Van der Waals repulsive forces serve as a barrier to particles, and so the problem of leakage is negligible. With proper pressure differentials between the actuator reservoir and the external environment, different magnitudes of force can be exerted and translated into movement through the Stewart platform tip. An assembler can utilize a matrix of Stewart platforms in order to create more assemblers.

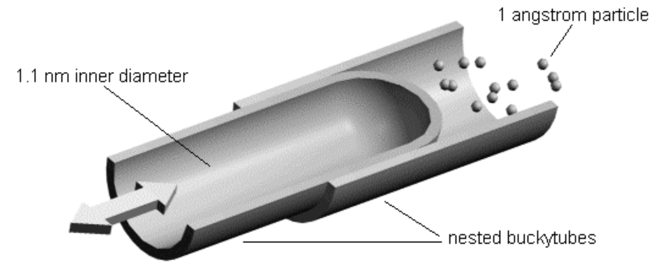


Figure 8: Molecular Actuator – *A carbon nanotube nested in an open buckytube can serve as a molecular actuator.*

The assembler operates essentially like a factory. A diamondoid wall encloses the 'factory floor,' which is either a vacuum or filled with inert gas. Each Stewart platform acts as a tool. If assembly were to take place exposed to the feedstock, it would limit the effectiveness of the Stewart platform. Exact construction would be difficult, if not impossible as molecules in the feedstock reacted with the molecular tool at the platform's tip. This enclosing wall also insulates the molecular actuators from the effects of change in external pressure.

One can think of MRN nanorobots as an active adhesive sealant. When a breach occurs, the robots literally tumble end-over-end to form a protective seal. In essence, space-filling polyhedra are equivalent to biological platelets. The mode of locomotion is characterized by repeated pivots about common edges, as the polyhedra are identical geometric structures.[17] An effective layer of these polyhedral nanorobots will be present in the Marssuit, so that time is not wasted in traveling to damaged areas. The first nanorobots arrive at the damaged area quickly, because they are directly adjacent to the damage. By either chemical or mechanical signal, the front line of nanorobots is signaled to anchor to the remaining suit material. This anchoring might be done with a tailored chemical reaction, forming a chemical bond with the suit and thus permanently anchoring the MRN.

By mechanical design, the nanorobots are capable of latching on to each other. As the repair progresses, the nanorobots begin to layer upon one another until they have formed a barrier around the damage. Tears should present little difficulty as the interlocking polyhedra can 'bridge' a small rip with minimal locomotion. Punctures are challenging due to possible outgassing, which would hinder the convergence of the nanorobots. With sufficiently strong mechanisms, a violently outgassing breach might be sealed, but a more elegant solution is preferable. By orienting the polyhedra such that they attach to the underside (facing the surface) of the Marssuit, successive waves of nanorobots can approach the previously established edge and then 'hang on.' For example, consider a circular puncture. As the SFP nanorobots repaired the hole, one would see the breach close in concentric circles.

Gas leakage is undoubtedly the most pressing concern in the event of suit damage. The MRN nanorobots' primary function is to seal the breach and therefore prevent rapid gas loss. Without going into detailed statistical mechanics, several arguments will suffice to place an upper bound on gas loss. Assuming that the nanorobots are cubic in shape and is Δ (arbitrary units) on a side, the effective area presented to an incident molecule is Δ^2. A likely choice for a wall material is the graphene sheet, which serves as a large potential (electrostatic, etc.) barrier to incident molecules. The gas loss through the MRN faces will be negligible compared to through the interfacial gaps. Let us now assume that the interfacial gap width is $\sigma = \Delta / 100$. For instance, a 50 nm gap (5000 nm MRN) is room aplenty for a variety of nanotube latching mechanisms. For a large number of nanorobots tessellating over a breach, the number of gaps per MRN approaches two. Then, neglecting the corner effects, the effective area for gas flow is reduced by a factor of $2\sigma\Delta / (\Delta^2 + 2\sigma\Delta) = 1/51$. About 2% of the initial area is available for leakage. Now consider that a 1 mm layer of nanorobots of Δ = 5,000 nm will have about 200 layers of MRNs. In the locality of a puncture the repair will probably be thicker than one millimeter, further attenuating the leakage. The specifics of the attenuation have to do with the 'lattice' configuration of the nanorobots. For the cubic nanorobots there is a straight path for molecules to take since the layers are not staggered, so we can expect a relatively low attenuation effect. Other geometries such as the rhombic dodecahedron do not present such a clear path for molecules to escape. For the more complex geometries, we can expect a quasi random-walk pattern to develop. Furthermore, the interfacial gap is not just open space – it is crowded by the MRN latching mechanisms. From this rough estimate we see that the MRN presence significantly lowers the leak rate. We also notice that the cubic configuration turns out to be the least desirable in terms of sealing effectiveness.

If the space filling polyhedra operate as desired, we can expect the resulting repair to be rather stiff like a scab. This is due to the space tessellation of the polyhedra, and the interlocking mechanisms. The question of brittle fracture arises when dealing with stiff materials. Because the nanorobots are built up in successive layers, the same toughening mechanism as with nanotube fiber composites is possible. That is, an advancing crack tip is deflected along the interfacial layers thereby reducing the stress concentration. Also, we must not forget that the MRNs form a dynamically reconfigurable barrier, so that if a crack manages to propagate past several layers of nanorobots, the repairing process will repeat anew. Ideally, the astronaut should deliberately avoid subjecting such a repair to high impact loads. Normal astronaut locomotion should not be effected by this repair, as the area around the repair should remain flexible enough to accommodate the 'scab.'

Let us now deal with the problem of dust. Atmospheric dust on Mars has a size range of about 50-100 μm.[18] Most of the dust directly on the Martian surface will be equivalent or greater in size. Since we have not yet committed to a specific size for the MRN nanorobots let us take a conservative estimate of 5,000 nm (5 μm), which is about the size of a human red blood cell. By this estimate, typical Martian dust is over ten times the size of a MRN. If a speck of dust is embedded such that it is not dislodged by outgassing, the nanorobots have little choice but to build up around the impediment. This is likened to a nail or thorn puncturing a tire that has a commercially available gel sealant – the breach is sealed despite the impediment. The same argument applies to larger penetrating objects as well.

Many mechanically useful nanoscale components have been developed that could be used to construct such polyhedral nanorobots. Once again, SWNT nanotubes are ideal structural members for nanometer construction. Researchers at Rice University have developed a method by which open nanotubes can be tethered to gold particles, forming useful mechanical linkages.[19] The perfection of this technique could allow us to construct a variety of polyhedral shaped structures. NASA researchers have modeled feasible gears from open nanotubes, and Merkle has simulated a viable molecular bearing.[20, 21] The inherently voluminous family of polyhedrons presents an ideal enclosure for mechanical logic components and fuel reserves.

Sensors

Nanometer-scale sensors will be difficult to design in the beginnings of nanorobotics. Sophistication in this area will develop with research – but this will take time. To decrease the time and research needed to develop this Marssuit repair system, only the simplest possible sensor arrays are used.

To implement the broadcast architecture for the assembler nanorobots, there must be a way to receive instructions. A molecular actuator (Figure 8) constructed of nested SWNT nanotubes can be easily modified for this purpose. Instead of modifying the internal pressure to produce an external effect on the actuator, the actuator is exposed to the pressures of the assembly tank. As the pressure changes, the actuator will move, which can be easily transmitted to the control system.

There are many different devices that sense position, from potentiometers to springs. Many of these can be scaled down effectively to the nanometer scale and used in nanorobotics. One approach to movement of the

Stewart platform (Figure 7) is to measure every aspect of its movement. Using a standard Proportional Integral Derivative (PID) control system, one can control the platform very accurately. However, due to the entire lack of friction on the molecular scale, if the pneumatics or engines to move the platform are very accurate, these sensory capabilities are not required. When using reasonably stiff structural elements, thermal noise will not cause more than a fraction of an atomic diameter of positional error, without explicit positional sensing.[5]

The capabilities required on the MRN nanorobot are quite different than those of the assembler. MRN nanorobots need to be able to make their way towards the site of suit damage, and detect the damage when they have reached it. To reduce sensor requirements as much as possible, MRN nanorobots can be programmed to act like gas molecules in many respects. Consider a box with a partition through the middle. One side is filled with gas at a certain pressure, while the other side is a vacuum. If the partition is removed, the gas molecules move towards the area of lower concentration. Because MRN nanorobots move randomly about common axes when a certain number of faces are not in contact with other nanorobots, they move naturally towards areas where there are few nanorobots because they are more free faces in that direction. Once damage occurs, there will be a local decrease in ‘pressure’ of MRN nanorobots, which will carry them towards the damage.

Once they reach the damage, they need to be able to recognize it. How this can be implemented depends considerably upon the material used. In any case, they should be able to sense a chemical difference between the surface of the fabric and the edge of the fabric, so they will know to bond to it. It is a more difficult problem to detect a MRN nanorobot that has bonded to the suit fabric. There are several ways of accomplishing this, including displaying the chemistry of the broken suit fabric on a face, so that other MRN nanorobots can detect it upon contact and will cease to pivot. Another method is extending claws or other small extremities that could be sensed on contact with other MRN nanorobots.

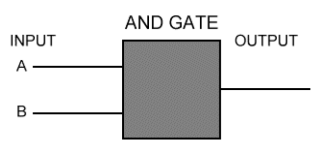
These contact signals are inherently directional, as the MRN nanorobots will adhere to the surface on which they detect them. To directionalize the repair towards the hole as opposed to making it essentially random, MRN nanorobots can display the signal on the face opposite to the one adhered to the previous MRN nanorobot. This way, they will repair more or less aligned with the damage, and can meet to seal the hole.

Control

Two basic types of logic have been designed for computers: mechanical and electrical. In nanocomputers, size is a major limitation. As electrons can tunnel through distances of a few nanometers, this greatly increases the minimum size of nanoelectric devices.[23] Mechanical logic devices can reach two nanometers before thermal noise makes them unreliable at room temperature.[24] Though nanoelectric devices will become feasible at some point, mechanical logic will likely precede it and remain as compact, low-speed logic and storage.

Conventional computer architectures use an irreversible architecture. This is a design in which one loses information during the course of a calculation, and so cannot deduce the inputs from the outputs (Figure 9). However, to effect this erasure of information requires $\ln(2)k_BT$ Joules of energy *per bit* to be dissipated as heat, where k_B is the Boltzmann constant and T is the absolute temperature.[2] Each *and* gate, for example, erases one bit of information. Macroscopic computers are designed to have enough airflow through them to dissipate this heat, but nanocomputers will not have this luxury. The energy dissipated as heat is lost energy from the system as well, requiring a greater energy input.

The solution to this problem is simply not to erase any information – to make the calculation *reversible*. Once the calculation is run, store the result and then run the calculation in reverse to ready the computer for another task. A reversible computer can be run with as little energy as desired, simply by running calculations more slowly to reduce friction, as the $\ln(2)k_BT$ limit does not apply.[24] There is probably some practical limit due to friction and molecular interaction, but this certainly lies far below the thermodynamic barrier.



A	B	Output
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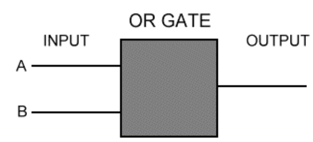
1	0	0
0	1	0
0	0	0



A	B	Output
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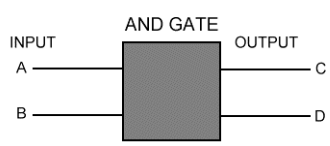
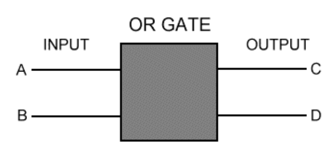
1	0	1
0	1	1
0	0	0



A	B	C	D
1	1	1	1
1	0	0	1
0	1	0	1
0	0	0	0



A	B	C	D
1	1	1	1
1	0	1	0
0	1	1	0
0	0	0	0

Figure 9: Conventional and Reversible Logic Gates – *Conventional logic gates (top) dissipate energy because they discard information. For example, if the output of an and gate is 0, there is no way to deduce definitely what the input was. Reversible logic gates (bottom) do not discard the unneeded bits (output D) and thus can be run reversibly, with minimal energy loss.*

A mechanically equivalent macroscopic logic device is a simple spring. Arbitrarily, the stretched state is defined as *1*, and the compressed state as *0*. While in its equilibrium state, the spring conveys no information. To represent a bit of information in the spring, one has to invest ½ kx^2 Joules, where k is the spring constant and x the displacement from equilibrium. In an irreversible architecture, once the bit has served its part in a calculation, it is erased. This is equivalent to the spring being released. As no spring is perfect, the oscillatory behavior will decay towards the equilibrium position. The ½ kx^2 invested in storing the information will be lost to friction, the second term in Equation 4.4.

Motion of a damped (frictional) spring:

$$m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = 0 \qquad \textbf{(4.4)}$$

However, if one restores the spring without releasing it, allowing the $-kx$ force from the spring to pull it back, the energy can be recovered. As this is not a perfect system, the frictional second term in Equation 4.4 does not allow the storage or recovery to be perfectly reversible. However, the frictional term b is proportional to dx/dt, or velocity. Therefore, reducing the speed at which the spring moves can reduce the energy lost to friction to any arbitrary level.

Several different types of mechanical reversible logic have been proposed. Drexler proposed "rod logic," where interlocking gates and knobs on rods perform Boolean logical operations reversibly.[25] (Figure 10) Merkle has proposed a scheme with bistable computing elements pulled by springs.[22] DeMara has developed a system with helical latches, reset springs, and rod assemblies.[26] Each of these forms of logical operations is a practical solution, and we shall not give preference to any of these schemes at this point.

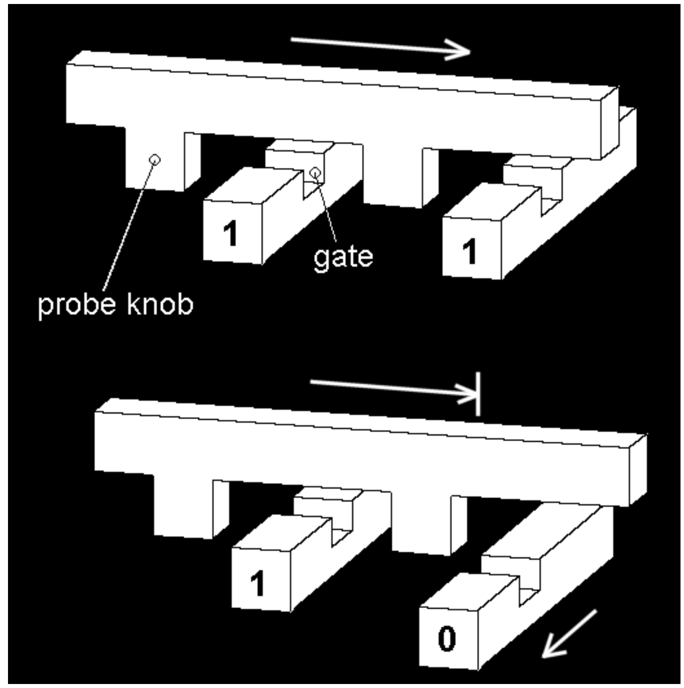


Figure 10: Rod Logic – *This **and** gate is an example of Drexler's rod logic. If both lower rods are in the **1** position (left), then the probe knobs pass through the gates when driven. This can be interpreted as a **1**. If both lower rods are not in the **1** position (right), the probe knobs cannot pass through the gates, and the upper rod cannot move. This can be interpreted as a **0**. Gates or other probe knobs can be attached to other faces of the rods, enabling this **and** gate to operate as part of a larger computer.*

Like the four components that make up a robot, five components make up a computer: input, output, memory, datapath, and control.[25] Sensor data is input, as instructions to the manipulator are output. Memory contains data and programs. Control directs the datapath, I/O, and memory. The datapath is the actual calculation mechanism.

Input is read directly from the sensors. If we are using mechanical logic, it is simple for the sensors to set mechanical devices to be read directly by the computer. This would involve a loss of at least $ln(2)k_BT$ per bit, but would be insignificant compared to the workings of the entire nanocomputer. Output can be handled in this way as well, by setting mechanical devices. These can stop motors or pneumatics, or restrict the motion of parts of the manipulator as needed. If needed, these can be operated reversibly in the manner of shared reversible mechanical memory, but the small number of bits needed for this uncomplicated manipulator render this unnecessary.[20]

Main memory can be implemented with latch rods or helices.[20, 24] If operated irreversibly, main memory would have to be kept extremely small because of the $\ln(2)k_BT$ Joule energy dissipation. Though the nanocomputers on both the assemblers and MRN nanorobots are quite simple, limiting main memory in this way would unnecessarily decrease the capabilities of these nanorobots and necessitate a complete redesign for any other model. Instead, operating memory reversibly can solve these problems and scale to more complex architectures as well. Once the information is computed and stored in main memory, to 'erase' the information, one simply recomputes the answer in memory. Then, the mechanical main memory latches can be released. This differs fundamentally from simply writing over the information, and thus losing it, because it is done reversibly and thus with as little energy loss as is required.[20]

Secondary storage is not required on MRN nanorobots, but to reduce the complexity of assembler calculations, we choose to add secondary memory to the assemblers. A feasible chemical storage involves using Hydrogen and Fluorine atoms at specified places along a polymer to represent the state *1* or *0*. A probe molecule, most feasibly $(CH_3)_3PO$, can be used like the head on a disk drive to read the state of the polymer and its embedded data.[26] As the entire computational task of the assembler is to interpret instructions from the macroscopic broadcasting computer, there is no need to write to secondary storage. The polymer can be fabricated, complete with data, during assembly. This polymer functions quite like a punched paper tape in an old mainframe. The data cannot be written except for when it is originally made, making it read-only memory. A head passes over it sequentially to determine whether each particular position represents the state *1* or *0*.

The datapath is constructed with reversible mechanical logic. The calculations must temporarily store intermediate values in order to reverse the computation and avoid losing information and the associated energy dissipation.

Control is handled quite differently in the assembler and the MRN nanorobot for reasons of safety. The assembler utilizes the broadcast architecture described earlier, with a macroscopic computer directing the actions of molecular assemblers. To enforce this model, control is tightly regulated in the assemblers. They have only just enough capability to receive an instruction from input and translate it into output instructions to the manipulator. There are a very limited set of instructions that control can utilize, so that a mistake in manufacture cannot lead to an "extraordinary accident." If an assembler is manufactured incorrectly, it cannot function without external instructions, and the worst-case scenario is the creation of flawed MRN nanorobots or assemblers that will be useless and harmless as well. It is far more probable that a flawed assembler will cease to function at all.

The control systems of MRN nanorobots are handled much in the manner of early computers, such as Babbage's Analytical Engine and other computers preceding the stored program concept.[11, 27] Before the stored program concept, all computers were either constructed for one particular task, or reprogrammed laboriously by rewiring the entire computer or basically reconstructing the entire mechanical computer. For the sake of both simplicity and safety, we choose to construct the MRN nanorobots the same way. They have no need for more than one task and so do not even need the option of reprogramming. In this way, they are not able to do anything more than their original programming.

MRN nanorobots should be tested before they are released into a suit. However, the worst-case scenario for a flawed MRN nanorobot is that it fails to repair a hole in the suit. As there are billions of other MRN nanorobots in the suit for exactly that purpose, the other ones will seal the hole, moving around the flawed one as an unmoving pivot.

These nanorobots cannot 'evolve' into a robot with capabilities the original does not have. The assemblers and MRN nanorobots are designed in such a way that any mistake in their fabrication simply flaws them beyond repair. As there are no useful forms that a 'mutation' can take, they cannot 'evolve.' Experiments show that computer programs virtually always simply fail to work if they are 'mutated,' and "unless they are specially designed, replicators directed by nanocomputers will share this handicap."[14]

Power Conversion

The first problem in power conversion is separating the fuel from the other molecules in the external environment. Drexler has proposed a "sorting rotor."[25] (Figure 11) This rotor is embedded in the diamondoid wall in such a way that as the cam turns, a portion of the rim will cycle from the outside environment to the inside. Around the rim of this rotor are variable-affinity binding sites for the desired molecule. These sites are controlled so that when they are exposed to the outer environment their affinity for the desired molecule is high, and when they are turned to the inside their affinity is low. A possible way to eliminate affinity while turned to the inside is simply to mechanically push a rod into the binding site, physically precluding occupancy.[29] Binding sites should have an extremely low affinity for all other molecules in the feedstock mixture. In this way, a section of the rim will turn to the external reservoir, adjust the binding sites for high affinity, and bind to the desired molecules. Once the cam has turned them to the internal reservoir, the binding sites are adjusted for low affinity for the desired molecule, and it unbinds and remains in the internal reservoir. By using several of these in a "cascade," the purity of the desired molecule in the final inner reservoir is extremely high, and the molecule can be presented in any orientation desired.

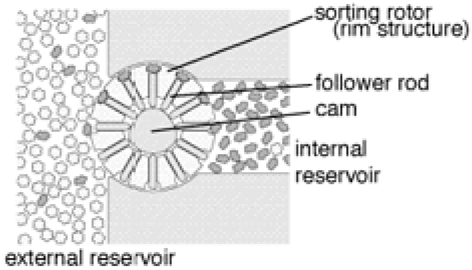


Figure 11: Sorting Rotor – *Variable affinity binding sites on a rotor make it possible to separate fuel and other molecules out of the feedstock. Operated in reverse, they can dispose of wastes.[23]*

Many molecules can serve as fuel. They can either be one-use molecules like hydrocarbons, or reusable fuels like Adenine Triphosphate (ATP). ATP is the energy storage unit used by the cells in animals. Three phosphate molecules are loosely bonded to the rest of the molecule, and breaking these bonds releases a manageable amount of energy, unlike the combustion of hydrocarbons. The ATP molecule, stripped of one or more of its phosphates, returns to have them re-added and more energy stored. This is a practical fuel model for nanorobotics because it releases manageable amounts of energy and the waste can be easily converted back into fuel by enzymes in the feedstock.

Waste removal can be handled in the same manner as fuel separation, except in reverse. Another rotor's binding sites can have high affinity for the waste molecules that result from the assembly process. When the cam rotates the sites to the external reservoir, the affinity of the sites for the waste molecules can be reduced, possibly by mechanically forcing a rod into the site. The waste molecules will disassociate from the binding sites and join the feedstock. To prevent the feedstock from becoming too high of a concentration of waste molecules, a filtration system can remove impurities and waste molecules. This can be achieved in a number of ways, including another set of rotors with variable-affinity binding sites. Wastes can be removed permanently from the feedstock, or used as raw material to make new molecules for the assemblers.

While this is quite practical for the assembler nanorobots, there is no feedstock to transport fuel molecules to the MRN nanorobots. It is possible to simply assemble the MRN nanorobots with a reservoir much like a fuel tank. Before the construction of this tank is completed, the assembler can simply fill it with fuel molecules. There are a few problems with this approach, however. The first is waste – if we supply the MRN nanorobot with enough fuel molecules for an extended stay in the suit, many of these molecules will not be used. Once a MRN nanorobot repairs damage to the suit, it simply becomes a part of the suit and essentially dead. It has no need for fuel in this state. Perhaps as a part of the repair process, it could open its fuel tank and let the molecules float free. This would only benefit MRN nanorobots in the immediate area, however, and many of the molecules will probably escape through the breach without being collected. If the MRN nanorobot has only enough fuel for a limited amount of activity, it must be removed to make room for other MRN nanorobots after its fuel has expired. Perhaps the layer the MRN nanorobots are to repair could be exchanged for a new one with fresh MRN nanorobots periodically or after extreme damage. The nanorobots could be equipped with a sensor for a certain chemical signal that will not occur in the suit naturally. This chemical signal is interpreted as an instruction to detach from the suit. They then become essentially dust which can be rinsed off the layer and replaced with fully fueled MRN nanorobots. It is more elegant to refuel the MRN nanorobots, but not strictly necessary. Once washed into the tank, the assemblers could be instructed by the macroscopic computer to open up the fuel tank and fill it again. After refueling, MRN nanorobots can again be returned to the suit. Without the feedstock to remove waste molecules, MRN nanorobots have to store their wastes on board. Another tank similar to the fuel tank, with easy access for the assemblers to empty it, could be added to the MRN nanorobots to store wastes.

Suit Integration

To obtain information about the operation of the MRN nanorobots, there must be some communication between the nanorobotic system and the rest of the suit. It is neither necessary nor desirable for an individual MRN to hold any information about its environment, but merely to move in accordance with its programming. Systems consisting of many objects with a simple behavior can exhibit a desirable "emergent behavior" if the simple behavior is carefully chosen. By putting the understanding of this emergent behavior in the suit rather in the individual MRN, we reduce complexity in the nanorobots, which are by far the most technologically difficult portion of the system.

Simple communications can be achieved by adding another molecular actuator to each face of an MRN which mates with a simple detector which can be pushed inwards by the actuator. We define the reception of a signal as when one of the detectors of an MRN is depressed a single time. A signal is propagated by actuating the molecular actuators of the other five faces, or some subset of these including the face opposite to the one on which the signal was received. If the received signal is propagated with a probability p ($0.5 < p < 1$), we will see a diminishing signal propagating roughly outwards from a source, with smaller signal waves washing back. Adding a small refractory period to the response will ensure that the signal will propagate little, if at all, in any but the radial direction. The probability of propagation includes such factors as having broken nanorobots in the system, who cannot pass on a signal, as well as foreign matter trapped in a matrix of MRN nanorobots, which will not propagate the signal. These signals do not need to be interpreted by the nanorobots they pass through, but simply passed on.

By embedding 'listening stations' in the fabric of the suit, these signals can be put to use. The MRN nanorobots that are adjacent to the fabric of the suit are propagating signals into it as part of their normal propagation process, and a simple receiver can capture the signals and send them back to the main suit processor for analysis. A listening station should be as large as several MRNs, so as not to be rendered vulnerable to being covered by a broken nanorobot and thereby having its signals blocked. By analyzing the signals reaching different locations, we can infer what is happening in different locations in the suit.

A signal is produced at the end of every move by an MRN. Normally, only a few MRN nanorobots will be moving at any one time, and these the farthest from the fabric surface. The signals captured by the listening station under these conditions will be relatively infrequent, as the signals degrade over time and distance and there are not a large number of them being produced. However, during the initial moments of a rip virtually all of the nanorobots in the area of the rip will be mobilized, putting out a very large number of signals, which are easily distinguishable from the signal received under normal conditions. Since a signal degrades over distance, those listening posts that are very close to the rip will receive far more signal pulses than those farther away. By using a system of triangulation based on signal duty cycle, the suit can infer the severity and location of damage.

CONCLUSIONS

Carbon nanotube materials can be used in many places where a light, strong material is required. The elastic properties and high tensile strength of nanotube fabrics makes for an ideal material in Marssuit construction. The toughening effect of crack deflection further augments the utility of nanotube matrix composites.

Used in combination, assemblers and MRN nanorobots compose a practical system for actively repairing Marssuit damage. Assemblers work within a feedstock environment, rich with fuel molecules and the raw materials with which to construct copies of both themselves and MRN nanorobots. A broadcast architecture sends signals from a central computer to each assembler through the liquid medium of the feedstock, ensuring safety and reducing the computational requirements of assemblers. Inside their 'factory floor' – either vacuum or inert gas – are an array of Stewart platforms constructed with molecular struts and SWNT nanotubes. Sensors include possible positional sensors to determine the position of the Stewart platforms, and a molecular actuator built of nested SWNT nanotubes to receive broadcast instructions. Fuel and raw materials are separated from the feedstock by a Drexler sorting rotor, and wastes removed in the same way.

MRN nanorobots act as space-filling polyhedra to repair the damage to a Marssuit. To reduce the need for sensors, they move in a random fashion like gas molecules. A local decrease in 'pressure' of nanorobots will carry them towards the damage, which they sense on contact with chemical sensors. Unable to receive fuel and dispose of wastes in the feedstock, they carry tanks with fuel molecules and wastes. If they are to be recycled, the assemblers can open the tanks, remove the wastes, and replenish the fuel.

Both types of nanorobots will utilize mechanical reversible logic. This will dramatically reduce both energy expenditure and heat dissipation, which is difficult on a molecular scale and could damage or disable the nanorobots. Assemblers will also have read-only chemical memory, implemented with a modified polymer and a chemical probe.

New materials such as SWNT nanotube composites have the potential of providing superior strength/weight ratios. Theoretical predictions and experimental observation indicate that carbon nanotubes have good elastic characteristics. Although nanotube composites have not yet been experimentally observed, we can infer their properties by comparison with similar materials such as carbon fiber or fiberglass. If the observed microscopic properties of nanotubes extend to macroscopic matrix composites, we can expect a new class of tough nanotube composites.

This system of assembler and MRN nanorobots utilizes a comparatively low level of nanoscale technology, which will make it feasible at the very beginning of our development of nanotechnology. MRN nanorobots will be able to seal damage to a Marssuit, allowing an astronaut time to return to the Mars habitat.

Decreased temperatures serve to increase the accuracy of positional devices, though they such devices can work in fairly high temperatures as well without excessive thermal variance. Dust, which can clog and disable macroscopic mechanical devices, has little effect on the function of MRNs. Assemblers, by building both themselves and MRN nanorobots, make the large number of MRN nanorobots economically feasible. This capability cannot become a danger, however, due to the broadcast architecture and dependence on the feedstock. Nanorobotics thus can be used safely and effectively to actively repair Marssuit damage.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

Å: angstrom (10^{-10} meters)
AFM: atomic force microscope
k_B**:** Boltzmann's Constant
MRN: Mars Repair Nanorobot
nm: nanometer (10^{-9} meters)
PID: proportional integral derivative
PLSS: portable life support system
SFP: space-filling polyhedra
SWNT, buckytube: single walled carbon nanotube
TPa: 10^{12} Pascals (N/m^2)