

UTILITY FOG: A UNIVERSAL PHYSICAL SUBSTANCE

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Abstract

Active, polymorphic material ("Utility Fog") can be designed as a conglomeration of 100-micron robotic cells ("foglets"). Such robots could be built with the techniques of molecular nanotechnology[18]. Controllers with processing capabilities of 1000 MIPS per cubic micron, and electric motors with power densities of one milliwatt per cubic micron are assumed. Utility Fog should be capable of simulating most everyday materials, dynamically changing its form and properties, and forms a substrate for an integrated virtual reality and telerobotics.

1 Introduction

Imagine a microscopic robot. It has a body about the size of a human cell and 12 arms sticking out in all directions. A bucketful of such robots might form a "robot crystal" by linking their arms up into a lattice structure. Now take a room, with people, furniture, and other objects in it— it's still mostly empty air. Fill the air completely full of robots.

With the right programming, the robots can exert any force in any direction on the surface of any object. They can support the object, so that it apparently floats in the air. They can support a person, applying the same pressures to the seat of the pants that a chair would. They can exert the same resisting forces that elbows and fingertips would receive from the arms and back of the chair. A program running in the Utility Fog can thus simulate the physical existence of an object.

The Utility Fog operates in two modes: First, the "naive" mode where the robots act much like cells, and each robot occupies a particular position and does a particular function in a given object. The second, or "Fog" mode, has the robots acting more like the pixels on a TV screen. The object is then formed of a *pat-*

tern of robots, which vary their properties according to which part of the object they are representing at the time. An object can then move across a cloud of robots without the individual robots moving, just as the pixels on a CRT remain stationary while pictures move around on the screen.

The Utility Fog which is simulating air needs to be impalpable. One would like to be able to walk through a Fog-filled room without the feeling of having been cast into a block of solid Lucite. It is also desirable to be able to breathe while using the Fog in this way! To this end, the robots representing empty space constantly run a fluid-flow simulation of what the air would be doing if the robots weren't there. Then each robot does what the air it displaces would do in its absence.

How can one breathe when the air is a solid mass of machines? Actually, it isn't really solid: the Foglets only occupy about 10% of the actual volume of the air (they need lots of "elbow room" to move around easily). There's plenty of air left to breathe. As far as physically breathing it, we set up a pressure-sensitive boundary which translates air motions on one side to Fog motions on the other. It might even be possible to have the Fog continue the air simulation all the way into the lungs.

To understand why we want to fill the air with microscopic robots only to go to so much trouble to make it seem as if they weren't there, consider the advantages of a TV or computer screen over an ordinary picture. Objects on the screen can appear and disappear at will; they are not constrained by the laws of physics. The whole scene can shift instantly from one apparent locale to another. Completely imaginary constructions, not possible to build in physical reality, could be commonplace. Virtually anything imaginable could be given tangible reality in a Utility Fog environment.

Why not, instead, build a virtual reality machine that produces a purely sensory (but indistinguishable)

version of the same apparent world? The Fog acts as a continuous bridge between actual physical reality and virtual reality. The Fog is universal effector as well as a universal sensor. Any (real) object in the Fog environment can be manipulated with an extremely wide array of patterns of pressure, force, and support; measured; analyzed; weighed; cut; reassembled; or reduced to bacteria-sized pieces and sorted for recycling.

2 General Properties and Uses

As well as forming an extension of the senses and muscles of individual people, the Fog can act as a generalized infrastructure for society at large. Fog City need have no permanent buildings of concrete, no roads of asphalt, no cars, trucks, or busses. It can look like a park, or a forest, or if the population is sufficiently whimsical, ancient Rome one day and Emerald City the next.

It will be more efficient to build dedicated machines for long distance energy and information propagation, and physical transport. For local use, and interface to the worldwide networks, the Fog is ideal for all of these functions. It can act as shelter, clothing, telephone, computer, and automobile. It will be almost any common household object, appearing from nowhere when needed (and disappearing afterwards). It gains a certain efficiency from this extreme of polymorphism; consider the number of hardcopy photographs necessary to store all the images one sees on a television or computer screen. With Utility Fog we can have one "display" and keep all our physical possessions on disk.

Another item of infrastructure that will become increasingly important in the future is information processing. Nanotechnology will allow us to build some really monster computers. Although each Foglet will possess a comparatively small processor—which is to say the power of a current-day supercomputer—there are about 16 million Foglets to a cubic inch. When those Foglets are not doing anything else, i.e. when they are simulating the interior of a solid object or air that nothing is passing through at the moment, they can be used as a computing resource (with the caveats below).

2.1 The Limits of Utility Fog Capability

When discussing something as far outside of everyday experience as the Utility Fog, it is a good idea to delineate both sides of the boundary. The Fog is capable of so many literally amazing things, we will point out a few of the things it isn't capable of:

- Anything requiring hard metal (cold steel?). For example, Fog couldn't simulate a drill bit cutting through hardwood. It would be able to cut the hole, but the process would be better described as intelligent sandpaper.

- Anything requiring both high strength and low volume. A parachute could not be made of Fog (unless, of course, all the air were filled with Fog, in which case one could simply fly).

- Anything requiring high heat. A Fog fire blazing merrily away on Fog logs in a fireplace would feel warm on the skin a few feet away; it would feel the same to a hand inserted into the "flame".

- Anything requiring molecular manipulation or chemical transformation. Foglets are simply on the wrong scale to play with atoms. In particular, they cannot reproduce themselves. On the other hand, they can do things like prepare food the same way a human cook does—by mixing, stirring, and using special-purpose devices that were designed for them to use.

- Fog cannot simulate food, or anything else that is destined to be broken down chemically. Eating it would be like eating the same amount of sand or sawdust.

- Fog can simulate air to the touch but not to the eyes. The best indications are that it would look like heavy fog. Thus the Fog would need to support a pair of holographic goggles in front of the eyes of an embedded user. Such goggles are clearly within the capabilities of the same level of nanotechnology as is needed for the Fog, but are beyond the scope of this paper.

2.2 Other Desirable Limitations

In 1611, William Shakespeare wrote his final play, "The Tempest." 445 years later, an obscure science fiction writer named W. J. Stuart updated the Tempest's plot into a story called "Forbidden Planet," and created a modern myth.

Forbidden Planet, more precisely the movie version, has become the classic cautionary tale for any scenario in which people become too powerful and control their environment too easily. In the story, the Krell are an ancient, wise, and highly advanced civilization. They perfect an enormous and powerful machine, capable of projecting objects and forces anywhere in any form, upon the mental commands of any Krell. The machine works "not wisely but too well," manifesting all the deeply buried subconscious desires of the Krell to destroy each other.

Utility Fog will provide humans with powers that approximate those of the fictional Krell machine.

Luckily, we have centuries of literary tradition to guide us around the pitfalls of hubris made reality. We must study this tradition, or we may be doomed to repeat it— a truth that is by no means limited to the Utility Fog, or indeed to nanotechnology in general.

The first thing we can do is to require fully conscious, unequivocal commands for the Fog to take any action. Beyond that, we can try to suggest some of the protocols that may be useful in managing the Fog in a situation where humans are interacting in close physical proximity. Even if we have solved the problem of translating one's individual wishes, however expressed, into the quadrillions of sets of instructions to individual Foglets to accomplish what one desired, the problem of who gets to control which Foglets is probably a much more contentious one.

We can physicalize the psychological concept of "personal space". The Foglets within some distance of each person would be under that person's exclusive control; personal spaces could not merge except by mutual consent. This single protocol could prevent most crimes of violence in our hypothetical Fog City.

A corollary point is that physically perpetrated theft would be impossible in a Fog world. It would still be possible by informational means, i.e. fraud, hacking, etc; but the Fog could be programmed to put ownership on the level of a physical law. —Not that it really makes any sense to think of stealing a fog-mode object, anyway. Ownership and control of the Fog need not be any more complex than the bundles of rights currently associated with everything from land to corporate stock.

Indeed, much of the programming of the Fog will need to have the character of physical laws. In order for the enormous potential complexity to be comprehensible and thus usable to human beings, it needs to be organized by simple but powerful principles, which must be consonant with the huge amount of hard-wired information processing our sensory systems perform. For example, it would be easy to move furniture (or buildings) by manipulating an appropriately sized scale model, and easy to observe the effects by watching the model. However, the Fog could just as easily have flooded the room with 100 kHz sound, and frequency-scaled the echoes down into the human auditory range. A bat would have no trouble with this kind of "scale model", but to humans it's just noise.

It will be necessary, in general, to arrange the overall control of the Fog to be extremely distributed, as local as possible, robust in the presence of failure. When we realize that a single cubic inch of Fog represents a computer network of 16 million processors, the

concept of hierarchical control with human oversight can be seen to be hopelessly inadequate. Agoric distributed control algorithms offer one possible solution.

2.3 Advantages of a Utility Fog Environment

Another major advantage for space-filling Fog is safety. In a car (or its nanotech descendant) Fog forms a dynamic form-fitting cushion that protects better than any seatbelt of nylon fibers. An appropriately built house filled with Fog could even protect its inhabitants from the (physical) effects of a nuclear weapon within 95% or so of its lethal blast area.

There are many more mundane ways the Fog can protect its occupants, not the least being physically to remove bacteria, mites, pollen, and so forth, from the air. A Fog-filled home would no longer be the place that most accidents happen. First, by performing most household tasks using Fog as an instrumentality, the cuts and falls that accompany the use of knives, power tools, ladders, and so forth, can be eliminated.

Secondly, the other major class of household accidents, young children who injure themselves out of ignorance, can be avoided by a number of means. A child who climbed over a stair rail would float harmlessly to the floor. A child could not pull a bookcase over on itself; falling over would not be among the bookcase's repertoire. Power tools, kitchen implements, and cleaning chemicals would not normally exist; they or their analogues would be called into existence when needed and vanish instead of having to be cleaned and put away.

Outside the home, the possibilities are, if anything, greater. One can easily imagine "industrial Fog" which forms a factory. It would consist of larger robots. Unlike domestic Fog, which would have the density and strength of balsa wood, industrial Fog could have bulk properties resembling hardwood or aluminum. A nanotechnology- age factory would probably consist of a mass of Fog with special-purpose reactors embedded in it, where high-energy chemical transformations could take place. All the physical manipulation, transport, assembly, and so forth would be done by the Fog.

2.4 Applications in Space Exploration

The major systems of spaceships will need to be made with special- purpose nanotechnological mechanisms, and indeed with such mechanisms pushed much closer to their true capacities than anything we have

talked about heretofore. In the spaceship's cabin, however, will be an acceleration couch. When not accelerating, which is most of the time, we'd prefer something useful, like empty space, there. The Utility Fog makes a better acceleration couch, anyway.

Fill the cabin with Utility Fog and never worry about floating out of reach of a handhold. Instruments, consoles, and cabinets for equipment and supplies are not needed. Non-simulable items can be embedded in the fog in what are apparently bulkheads.

The Fog can add great structural strength to the ship itself; the rest of the structure need be not much more than a balloon. The same is true for spacesuits: Fog inside the suit manages the air pressure and makes motion easy; Fog outside gives extremely fine manipulating ability for various tasks. Of course, like the ship, the suit contains many special purpose non-Fog mechanisms.

Surround the space station with Fog. It needs radiation shielding anyway (if the occupants are long-term); use big industrial Foglets with lots of redundancy in the mechanism; even so they may get recycled fairly often. All the stock problems from SF movies go away: humans never need go outside merely to fix something; when EVA is desired for transfer or recreation, outside Fog provides complete safety and motion control. It also makes a good tugboat for docking spaceships.

Homesteaders on the Moon could bring along a batch of heavy duty Fog as well as the special-purpose nanotech power generation and waste recycling equipment. There will be a million and one things, of the ordinary yet arduous physical task kind, that must be done to set up and maintain a self-sufficient household.

3 Physical Properties of Utility Fog

Most currently proposed nanotechnological designs are based on carbon. Carbon is a marvelous atom for structural purposes, forming a crystal (diamond) which is very stiff and strong. However, a Fog built of diamond would have a problem which nanomechanical designs of a more conventional form do not pose: the Fog has so much surface area exposed to the air that if it were largely diamond, especially on the surface, it would amount to a "fuel-air explosive".

Therefore the Foglet is designed so that its structural elements, forming the major component of its mass, are made of aluminum oxide, a refractory compound using common elements. The structural elements form an exoskeleton, which besides being a good

mechanical design allows us to have an evacuated interior in which more sensitive nanomechanical components can operate. Of course, any macroscopic ignition source would vaporize the entire Foglet; but as long as more energy is used vaporizing the exoskeleton than is gained burning the carbon-based components inside, the reaction cannot spread.

Each Foglet has twelve arms, arranged as the faces of a dodecahedron. The arms telescope rather than having joints. The arms swivel on a universal joint at the base, and the gripper at the end can rotate about the arm's axis. Each arm thus has four degrees of freedom, plus opening and closing the gripper. The only load-carrying motor on each axis is the extension/retraction motor. The swivel and rotate axes are weakly driven, able to position the arm in free air but not drive any kind of load; however, there are load-holding brakes on these axes.

The gripper is a hexagonal structure with three fingers, mounted on alternating faces of the hexagon. Two Foglets "grasp hands" in an interleaved six-finger grip. Since the fingers are designed to match the end of the other arm, this provides a relatively rigid connection; forces are only transmitted axially through the grip.

When at rest, the Foglets form a regular lattice structure. If the bodies of the Foglets are thought of as atoms, it is a "face-centered cubic" crystal formation, where each atom touches 12 other atoms. Consider the arms of the Foglets as the girders of the trusswork of a bridge: they form the configuration known as the "octet truss" invented by Buckminster Fuller in 1956. The spaces bounded by the arms form alternate tetrahedrons and octahedrons, both of which are rigid shapes.

The Fog may be thought of as consisting of layers of Foglets. The layers, and the shear planes they define, lie at 4 major angles (corresponding to the faces of the tetrahedrons and octahedrons) and 3 minor ones (corresponding to the face-centered cube faces). In each of the 4 major orientations, each Foglet uses six arms to hold its neighbors in the layer; layers are thus a 2-dimensionally rigid fabric of equilateral triangles. In face-centered mode, the layers work out to be square grids, and are thus not rigid, a slight disadvantage. Most Fog motion is organized in layers; layers slide by passing each other down hand-over-hand in bucket brigade fashion. At any instant, roughly half the arms will be linked between layers when they are in motion.

The Fog moves an object by setting up a seed-shaped zone around it. The Foglets in the zone move with the object, forming a fairing which makes the

motions around it smoother. If the object is moving fast, the Fog around its path will compress to let it go by. The air does not have time to move in the Fog matrix and so the motion is fairly efficient. For slower motions, efficiency is not so important, but if we wish to prevent slow-moving high-pressure areas from interfering with other airflow operations, we can enclose the object's zone in a self-contained convection cell which moves Foglets from in front to behind it.

Each moving layer of robots is similarly passing the next layer along, so each layer adds another increment of the velocity difference of adjacent layers. Motors for arm extension can run at a gigahertz, and be geared down by a factor of 100 to the main screw in the arm. This will have a pitch of about a micron, giving a linear extension/retraction rate of about 10 meters per second. We can estimate the inter-layer shear rate at this velocity; the foglets are essentially pulling themselves along. Thus for a 100-micron interlayer distance Fog can sustain a 100 meter-per-second shear per millimeter of thickness.

The atomically-precise crystals of the Foglets' structural members will have a tensile strength of at least 100,000 psi (i.e. high for steel but low for the materials, including some fairly refractory ceramics, used in modern "high-tech" composites). At arms length of 100 microns, the Fog will occupy 10% of the volume of the air but has structural efficiency of only about 1% in any given direction.

Thus Utility Fog as a bulk material will have a density (specific gravity) of 0.2; for comparison, balsa wood is about 0.15 and cork is about 0.25. Fog will have a tensile strength of only 1000 psi; this is about the same as low-density polyethylene (solid, not foam). The material properties arising from the lattice structure are more or less isotropic; the one exception is that when Fog is flowing, tensile strength perpendicular to the shear plane is cut roughly in half.

Without altering the lattice connectivity, Fog can contract by up to about 40% in any linear dimension, reducing its overall volume (and increasing its density) by a factor of five. (This is of course done by retracting all arms but not letting go.) In this state the fog has the density of water. An even denser state can be attained by forming two interpenetrating lattices and retracting; at this point its density and strength would both be similar to ivory or Corian structural plastic, at specific gravity of 2 and about 6000 psi. Such high-density Fog would have the useful property of being waterproof (which ordinary Fog is not), but it cannot flow and takes much longer to change configuration.

3.1 Foglets in Detail

Foglets run on electricity, but they store hydrogen as an energy buffer. We pick hydrogen in part because it's almost certain to be a fuel of choice in the nanotech world, and thus we can be sure that the process of converting hydrogen and oxygen to water and energy, as well as the process of converting energy and water to hydrogen and oxygen, will be well understood. That means we'll be able to do them efficiently, which is of prime importance.

Suppose that the Fog is flowing, layers sliding against each other, and some force is being transmitted through the flow. This would happen any time the Fog moved some non-Fog object, for example. Just as human muscles oppose each other when holding something tightly, opposing forces along different Foglet arms act to hold the Fog's shape and supply the required motion.

When two layers of Fog move past each other, the arms between may need to move as many as 100 thousand times per second. Now if each of those motions were dissipative, and the fog were under full load, it would need to consume 700 kilowatts per cubic centimeter. This is roughly the power dissipation in a .45 caliber cartridge in the millisecond after the trigger is pulled; i.e. it just won't do.

But nowhere near this amount of energy is being used; the pushing arms are supplying this much but the arms being pushed are *receiving* almost the same amount, minus the work being done on the object being moved. So if the motors can act as generators when they're being pushed, each Foglet's energy budget is nearly balanced. Because these are arms instead of wheels, the intake and outflow do not match at any given instant, even though they average out the same over time (measured in tens of microseconds). Some buffering is needed. Hence the hydrogen.

I should hasten to add that almost never would one expect the Fog to move actively at 1000 psi; the pressure in the column of Fog beneath, say, a "levitated" human body is less than one thousandth of that. The 1000 psi capability is to allow the Fog can simulate hard objects, where forces can be concentrated into very small areas. Even so, current exploratory engineering designs for electric motors have power conversion densities up to a billion watts per cubic centimeter, and dissipative inefficiencies in the 10 parts per million range. This means that if the Empire State Building were being floated around on a column of Fog, the Fog would dissipate less than a watt per cubic centimeter.

Moving Fog will dissipate energy by air turbulence

and viscous drag. In the large, air will be entrained in the layers of moving Fog and forced into laminar flow. Energy consumed in this regime may be properly thought of as necessary for the desired motion no matter how it was done. As for the waving of the arms between layers, the Reynolds number decreases linearly with the size of the arm. Since the absolute velocity of the arms is low, i.e. 1 m/s, the Reynolds number should be well below the "lower critical" value, and the arms should be operating in a perfectly viscous regime with no turbulence. The remaining effect, viscous drag (on the waving arms) comes to a few watts per square meter of shear plane per layer.

There will certainly be some waste heat generated by Fog at work that will need to be dissipated. This and other applications for heat pumps, such as heating or cooling people (no need to heat the whole house, especially since some people prefer different temperatures), can be done simply by running a flow of Fog through a pipe-like volume which changes in area, compressing and expanding the entrained air at the appropriate places.

3.2 Communications and Control

In the macroscopic world, microcomputer-based controllers (e.g. the widely used Intel 8051 series microcontrollers) typically run on a clock speed of about 10 MHz. They emit control signals, at most, on the order of 10 KHz (usually less), and control motions in robots that are at most 10 Hz, i.e. a complete motion taking one tenth of a second. This million-clocks-per-action is not strictly necessary, of course; but it gives us some concept of the action rate we might expect for a given computer clock rate in a digitally controlled nanorobot.

Drexler's carefully detailed analysis shows that it is possible to build *mechanical* nanocomputers with gigahertz clock rates. Thus we can immediately expect to build a nanocontroller which can direct a 10 kilohertz robot. However, we can do better.

Since the early microcontrollers were developed, computer architecture has advanced. The 8051's do 1 instruction per 6, 12, or 18 clock cycles; modern RISC architectures execute 1 instruction per cycle. So far, nobody has bothered to build a RISC microcontroller, since they already have more computing power than they need. Furthermore, RISC designs are efficient in hardware as well as time; one early RISC was implemented on a 10,000-gate gate array. This design could be translated into rod logic in less than one tenth of one percent of a cubic micron.

Each Foglet is going to have 12 arms with three axis control each. In current technology it isn't uncommon to have a processor *per axis*; we could fit 36 processors into the Foglet but it isn't necessary. The tradeoffs in macroscopic robotics today are such that processors are cheap; in the Foglet things are different. The control of the arms is actually much simpler than control of a macroscopic robot. They can be managed by much simpler controllers that take commands like "Move to point X at speed y." Using a RISC design allows a single processor to control a 100 kHz arm; using auxilliary controllers will let it do all 12 easily.

But there is still a problem: Each computer, even with the power-reducing reversible logic designs espoused by Drexler, Merkle, and this author, is going to dissipate a few nanowatts. At a trillion foglets per cubic meter, this is a few kilowatts per cubic meter. Cooling for such a dissipation must needs be somewhere between substantial and heroic. As long as the computers can go into a standby mode when the Fog is standing still, however, this is quite workable. Concentrations of heavy work, mechanical or computing, would still require cooling circulation to some degree, but, as we have seen, the Fog is perfectly capable of doing that.

What about all the other computing overhead for the Fog? Besides the individual control of its robotic self, each Foglet will have to run a portion of the overall distributed control and communications algorithms. We can do another clock-speed to capability analogy from current computers regarding communications. Megahertz-speed computers find themselves well employed managing a handful of megabit data lines. Again we are forced to abandon the engineering tradeoffs of the macroscopic world: routing of a message through any given node need theoretically consume only a handful of thermodynamically irreversible bit operations; typical communications controllers take millions. Special-purpose message routers designed with these facts in mind must be a part of the Foglet.

If the Fog were configured as a store-and-forward network, packets with an average length of 100 bytes and a 1000-instruction overhead, information would move through the Fog at 50 meters/second, i.e. 110 mph. It represents a highly inefficient use of computation even with special-purpose hardware. It will be necessary to design a more efficient communication protocol. Setting up "virtual circuits" in the Fog and using optical repeaters (or simply mechanically switching the optical waveguides) should help considerably.

3.3 Synergistic Combination with Other Technologies

The counterintuitive inefficiency in communications is an example, possibly the most extreme one, of a case where macroscopic mechanisms outperform the Fog at some specific task. This will be even more true when we consider nano-engineered macroscopic mechanisms.

We could imagine a robot, human-sized, that was formed of a collection of nano-engineered parts held together by a mass of Utility Fog. The parts might include "bones", perhaps diamond-fiber composites, having great structural strength; motors, power sources, and so forth. The parts would form a sort of erector set that the surrounding Fog would assemble to perform the task at hand. The Fog could do directly all subtasks not requiring the excessive strength, power, and so forth that the special-purpose parts would supply.

The Fog house, or city, would resemble the Fog robot in that regard. The roof of a house might well be specially engineered for qualities of waterproofness, solar energy collection, and resistance to general abuse, far exceeding that which ordinary general purpose Fog would have. (On the other hand, the Fog could, if desired, have excellent insulating properties.) Of course the roof need not be one piece—it might be inch-square tiles held in place by the supporting Fog, and thus be quite amenable to rearrangement at the owner's whim, incremental repair and replacement, and all the other advantages we expect from a Fog house.

Another major component that would be special-purpose would be power and communications. Working on more-efficient protocols such as suggested above, the Fog would form an acceptable communications link from a person to some terminal in the same building; but it would be extremely inefficient for long-haul, high bandwidth connections such as that needed for telepresence.

Power is also almost certainly the domain of special-purpose nano-engineered mechanisms. Power transmission in the Fog is likely to be limited, although for different reasons from data transmission. Nanotechnology will give us an amazing array of power generation and distribution possibilities, and the Fog can use most of them.

The critical heterogeneous component of Fog is the Fog-producing machine. Foglets are not self-reproducing; there is no need for them to be, and it would complicate their design enormously to give them fine atom-manipulating capability. One imagines a Fog machine the size of a breadbox producing

Fog for a house, or building-sized machines filling cities with Fog. The Fog itself, of course, conveys raw materials back to the machine.

Acknowledgements

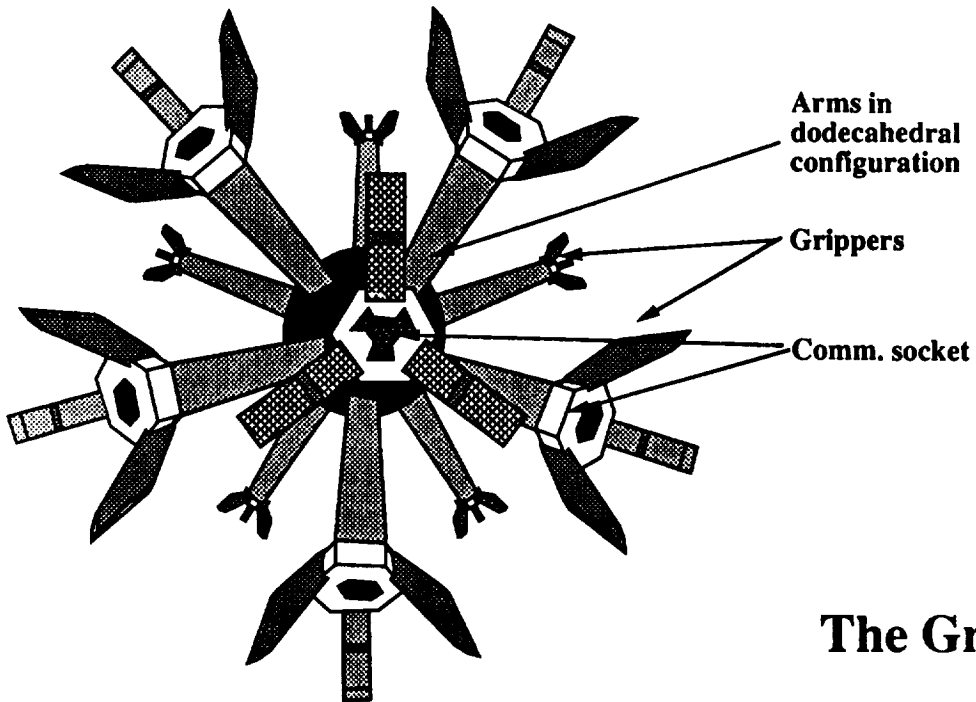
Many thanks to Carl Feynman who analyzed the Fog and made numerous suggestions.

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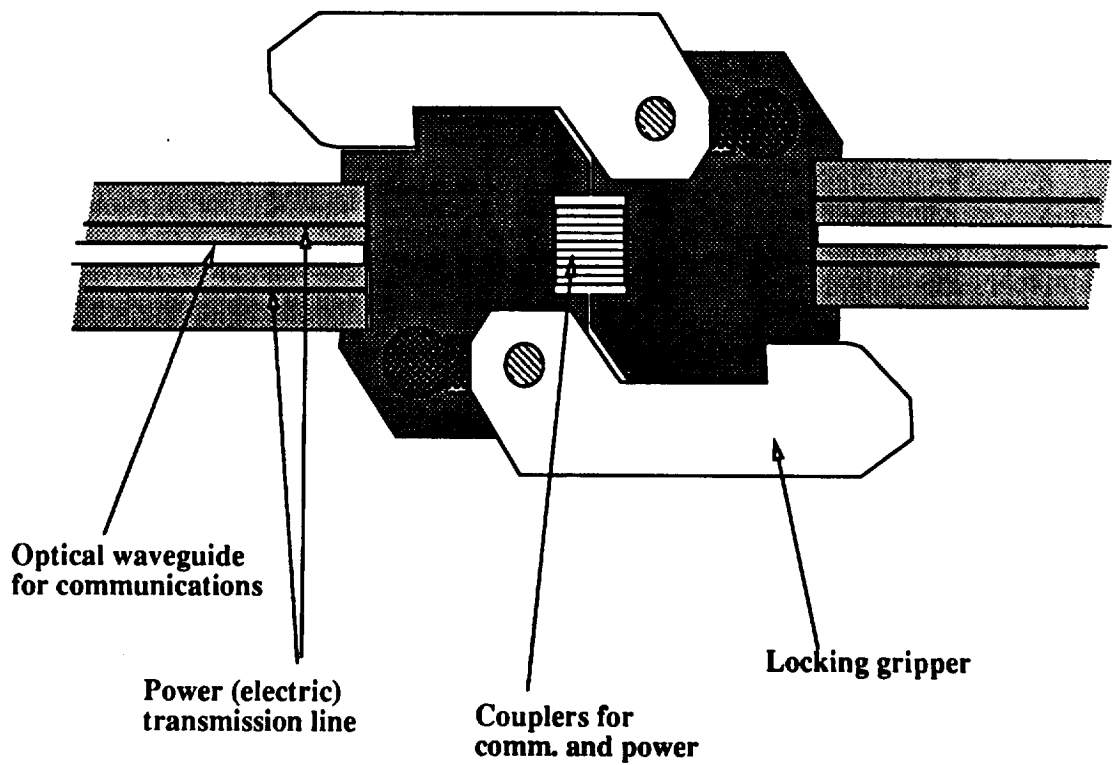
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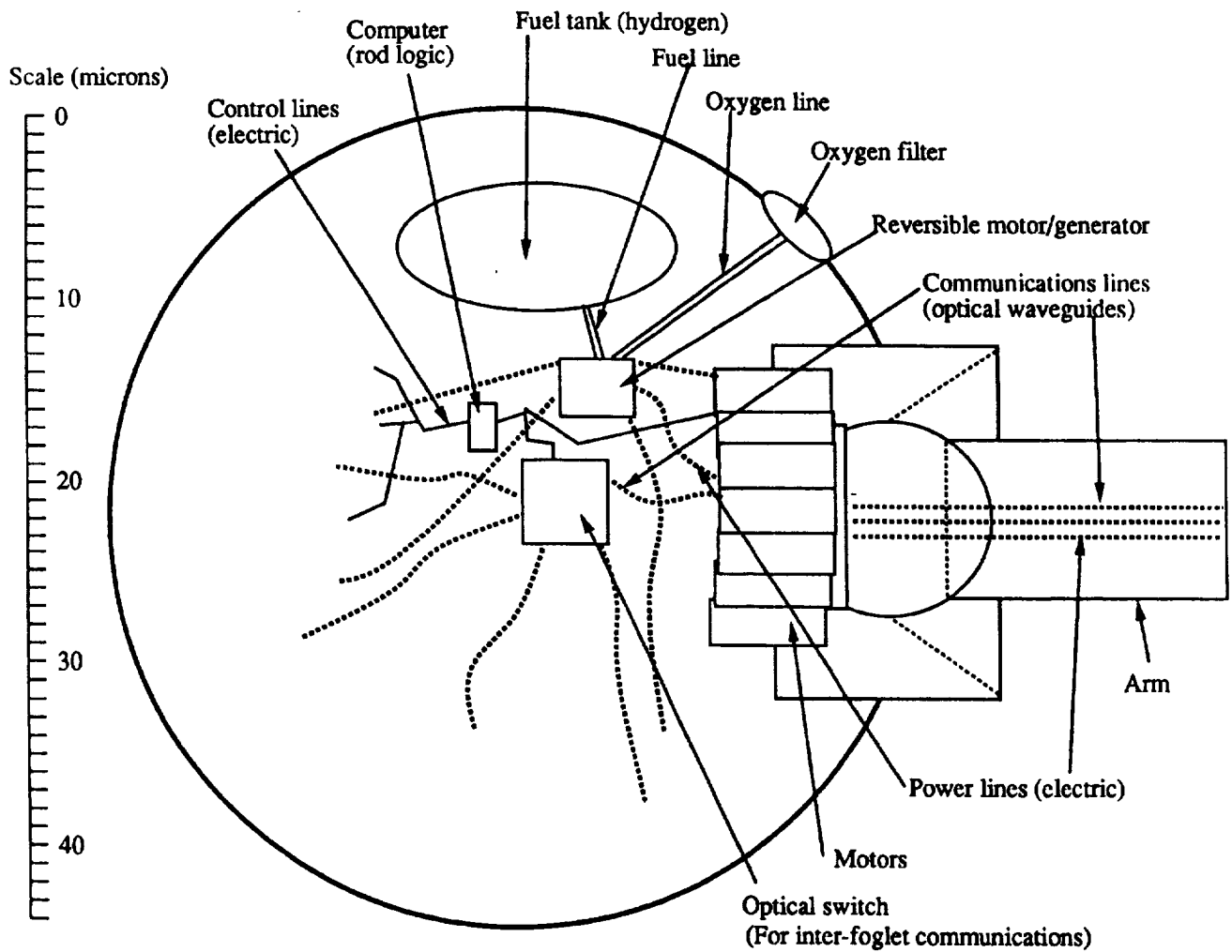
A Foglet



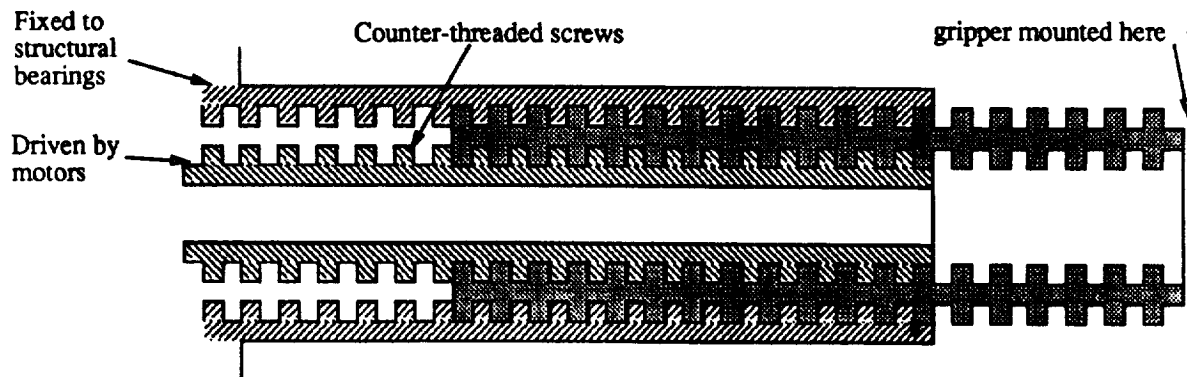
The Grip



Foglet Internals -- schematic (more or less to scale)

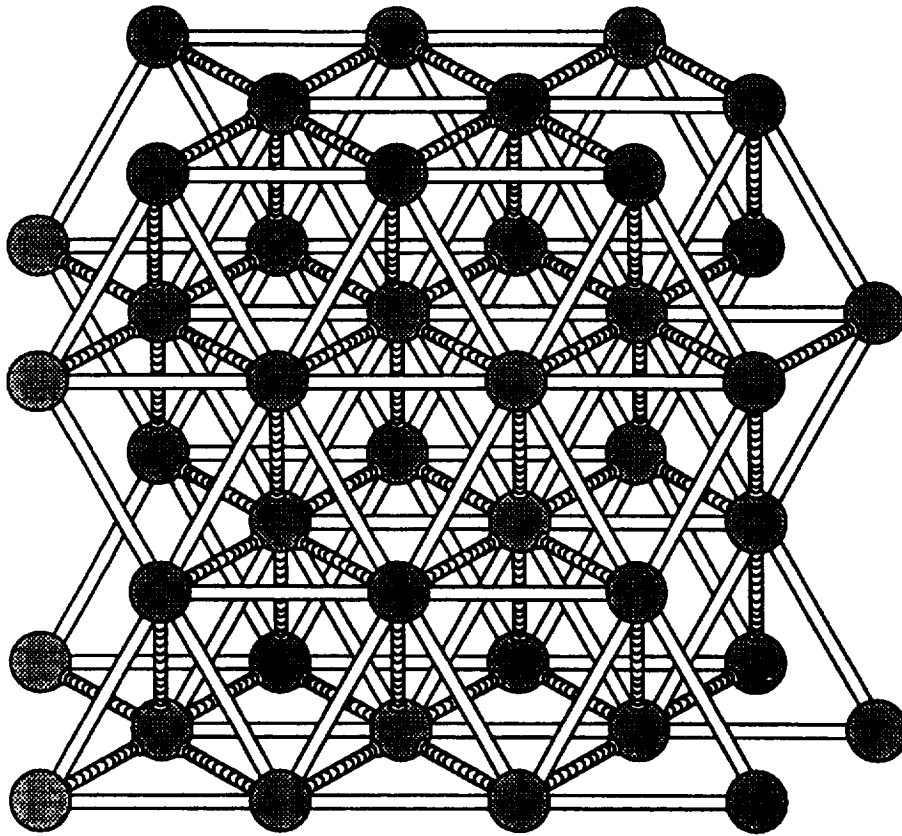


Arm extension (detail)

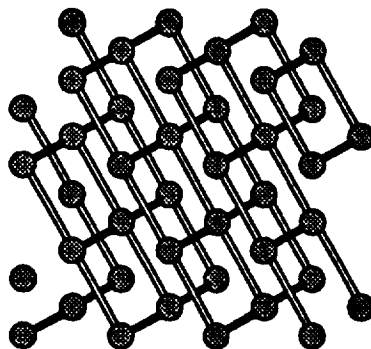
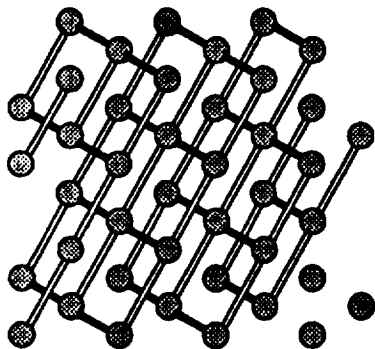


With atomically-precise surfaces the screws should be almost completely frictionless.

Three layers of Foglets

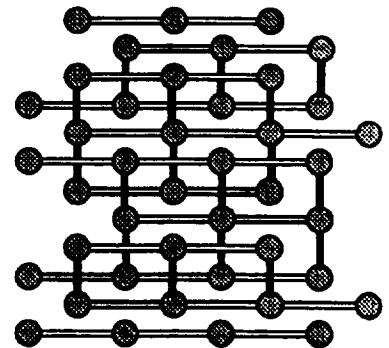
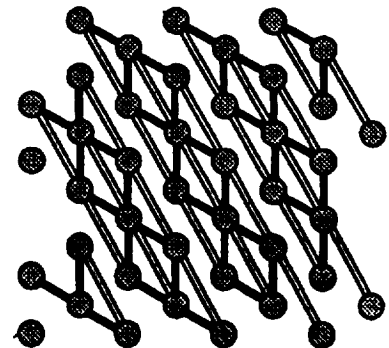
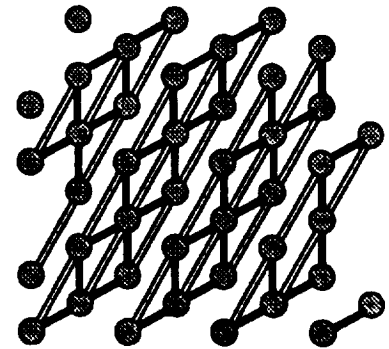
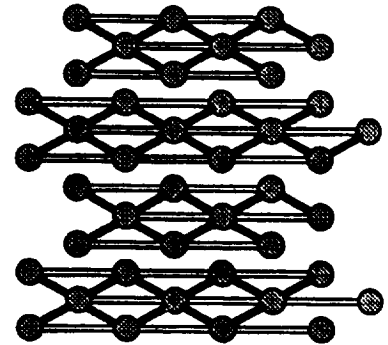


This shows the lattice structure assumed by a mass of Foglets. Only three of the Foglets in this picture are shown with all their arms. Grippers are not shown at all.



3 of the 4 major shear planes and the 3 minor ones. The other major (triangular) plane is parallel to the page. There is no rectangular shear plane parallel to the page.

Shear planes for moving layers



The flow of Fog around a moving object

