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A Proposed MNT Active Cell

By Forrest Bishop

(0) Abstract

Molecular nanotechnology may allow the construction of atomically precise structures. One such structure of interest is a space-filling polyhedral cell, with interfaces and drive systems on each of its faces that allow it to interact with other identical cells, or "active cells". A robot constructed in this manner can have a very large and detailed envelope of motion.

A cubical "active cell "design, built by molecular nanotechnology means is described and characterized. The mechanical interfaces, power and signal interfaces, and so forth are outlined in this baseline design. One mechanical and three electrostatic drive mechanisms are proposed. Some requirements for the control software for a connected collection of these active cells are considered. A few applications are mentioned, as well as a proposed manufacturing method.

Figures

(1) Introduction

An "active cell" is defined here as a space-filling polyhedral construct having power, signal, drive, and mechanical interfaces on each face of the cell [2]. A connected collection, or aggregate, of these cells form a "kinetic cellular automaton" capable of assuming many different configurations [3].

This baseline design is an "XY cube" with a nominal edge length, or cell metric, of 167 nanometers (Fig **1**). Here 'XY' (and 'Z') refers to the local coordinate system of the particular face of the cube under consideration, not to any global coordinates. The principle reason for the selection of the cell metric was to adhere to the design rules in [1], especially regarding size and spacing of conductors. It should not represent a lower bound on the size of an active cell. Secondary constraints include steric and structural considerations [4], as well as the size of the included motor and controller.

The structural material is of the diamondoid class, assembled by the putative methods of molecular manufacturing [1]. Each active cell contains an internal Drexler "rod logic" [1] controller to perform various housekeeping functions, as well as to communicate with its neighboring cells.

There is, in addition to the controller, an internal electromechanical interface switch for power and signals (FIG **2**). Energy is delivered to the cell electrically, via roller contacts. The drive system looked at in some detail is a linear electrostatic motor derivative. The conductor material is unfortunately not specified. As the electrical lead and contact resistances cannot be fully characterized [5-8], a programmable voltage multiplier is incorporated to keep the cell-to-cell energy transfer at the nominal voltage. This imposes a major signal propagation delay, which might be decreased, even to the theoretical limit (with superconductors), in a more refined design.

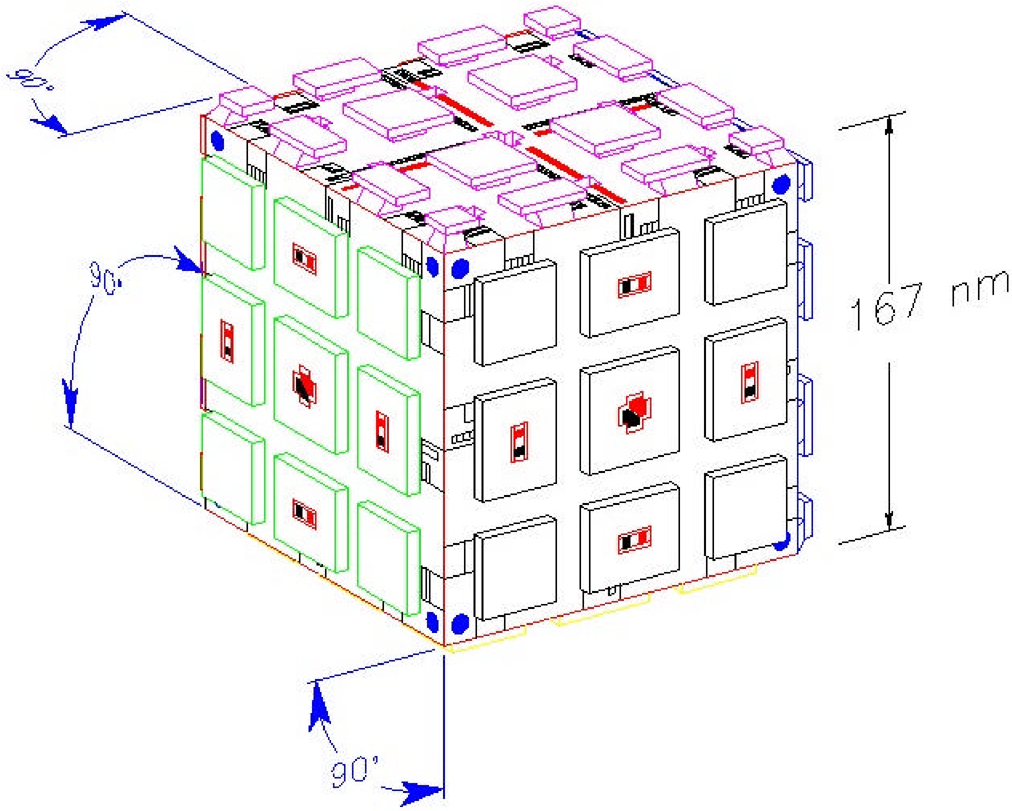

Figure (1)

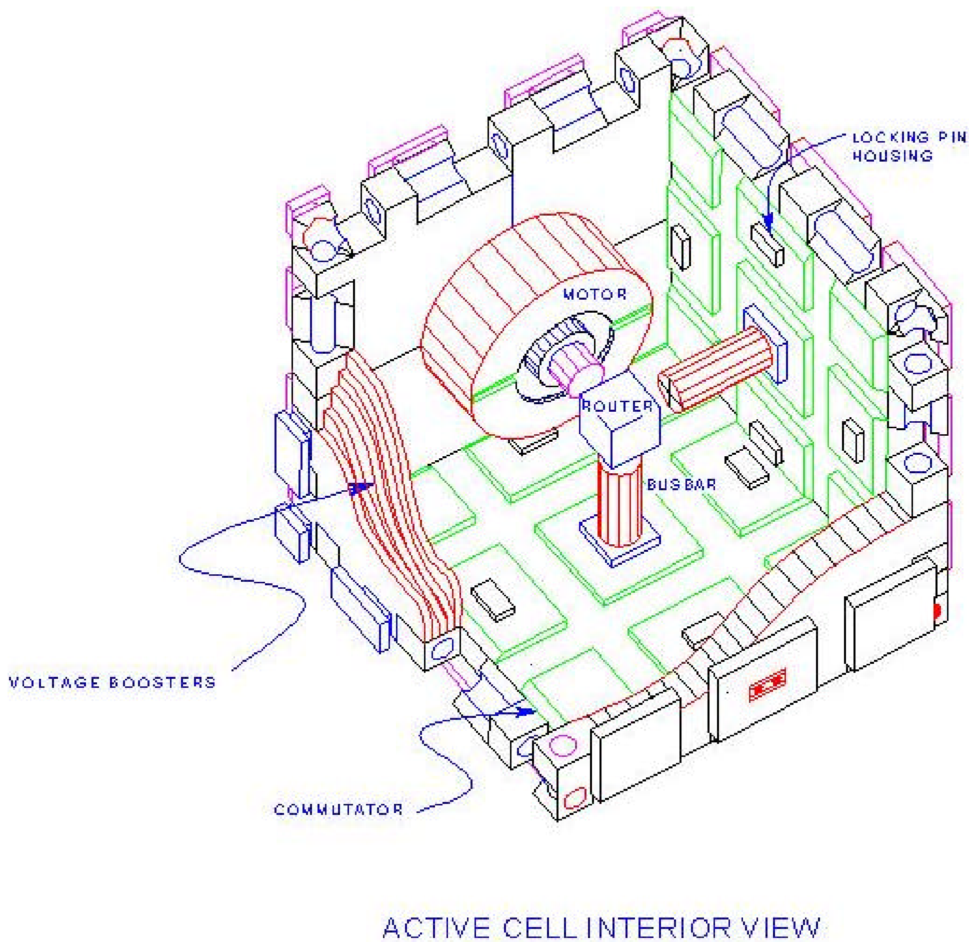

Figure (2)

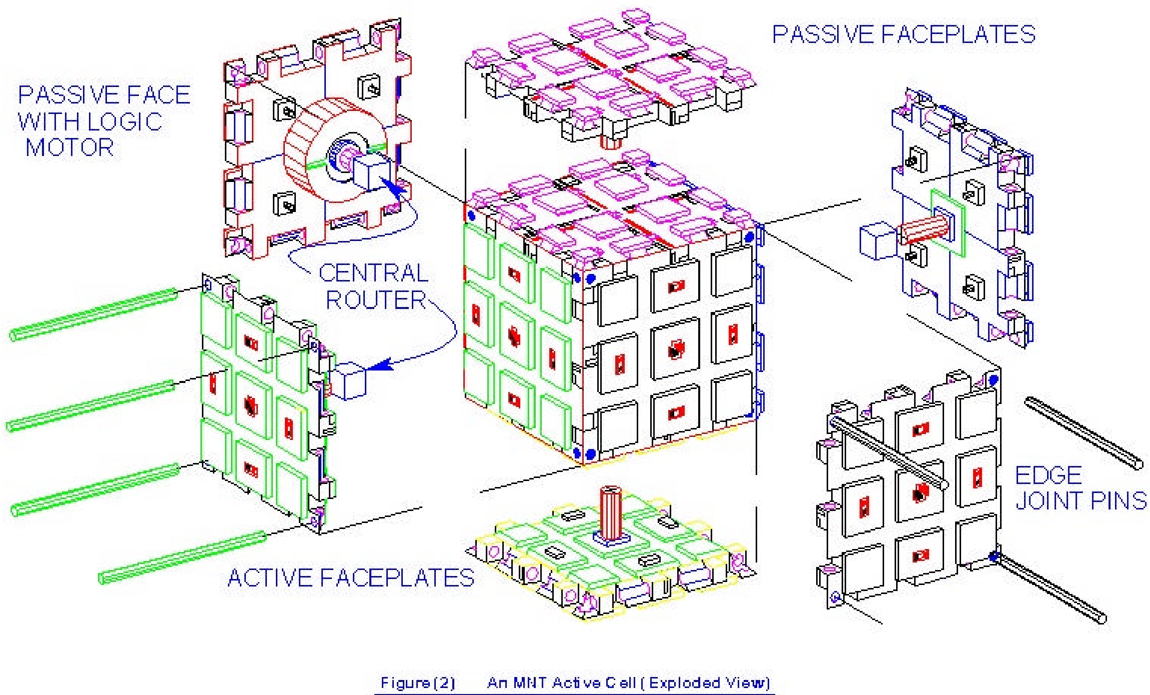

Figure (2a)

As this is a study design, the various parameters involved are not optimized. The intent is to illustrate what might be accomplished, not -by any stretch- to say how it should be done.

It should be noted that a system composed of these kinds of active cells may form the core of (in addition to a Universal Assembler [9,10]) a research facility inquiring into many aspects of atomic-scale engineering.

(2) XY Cube Mechanical Description

An XY cube is a cubicle active cell with mechanical interfaces on each of the six faces that allow the mutual sliding of two connected cubes in one of the two directions parallel to the joined faces, and parallel to the edges of those faces [2]. The two faces of each sliding cube that are parallel to the motion and perpendicular to the join plane remain flush to the corresponding faces on the other cube. The cubes are unable to detach the two joined faces by movement normal to the plane of the joint. They can only move in one of the two permitted directions at a time, and must be aligned with four faces flush in order to change direction. They do not rotate in any manner with respect to one another (FIG **1**).

The mechanical interfaces consist of orthogonal "T-slots" cut into a face of a cube. The slots are parallel to the edge of the face, and actually form "T-posts" [11] when both sets of slots are considered. There are two complementary sets of these T-posts, and each cube has one type ("active faceplate") on three of its adjoining faces, and the other type ("passive faceplate") on its other three adjoining faces. Although the number of T-posts is somewhat arbitrary, the reference design uses nine T-posts on the active face, and 16 T-posts on the passive face. The twelve posts on the perimeter of the passive face do not have "shelves" extending from their outboard sides. As this is a general purpose, or generic, design, little attempt is made to equalize cross-sections, or to minimize stress in a particular plane.

These features of an XY cube introduce a chirality to the aggregate, and a specific orientation for mutual interfacing. As there are no permitted modes of rotation, this internal orientation is maintained regardless of the configuration of the aggregate. An active face is therefore always adjoining a passive face.

When two XY cubes are interfaced and aligned, some method of locking them together is desirable. This might be done piezoelectrically (e.g. warping the T-posts), but the baseline design uses four tapered, retractable locking pins extending from one cell to complementary holes in another. There are other mechanical methods of accomplishing the same thing.

In order to move in the 'X' or 'Y' direction, the two pins on the axis perpendicular to the desired movement are first withdrawn. With the drive engaged, the two pins in line with the movement, which have tapers in this direction, are then withdrawn at some controlled rate.. Owing to this taper, the cell begins its movement before the pins are fully withdrawn. The purpose of all this activity is to prevent the cell from wedging by rotating about the local 'Z' axis. Once the cell moves out of the aligned rest position, this is no longer a major issue.

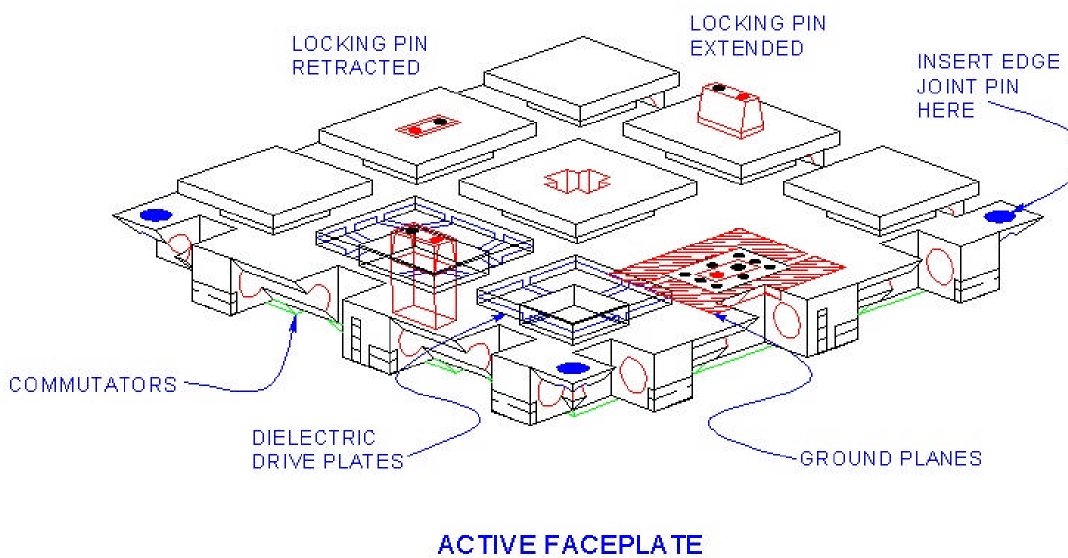

Figure (3)

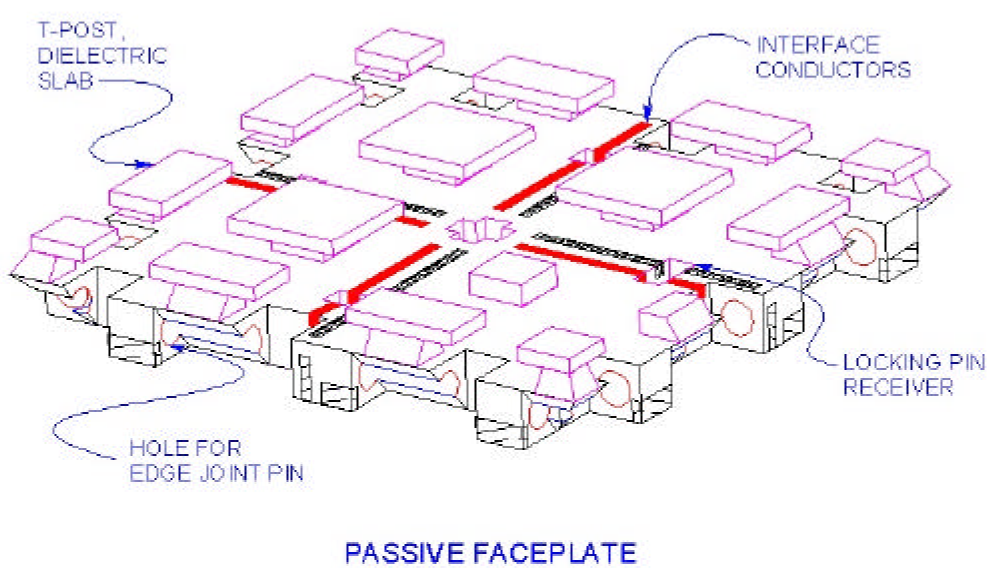

Figure (4)

With the electrostatic drive systems outlined below, an active cell can be built that has no breaches, or holes, through the cell wall, an advantage in environments such as air. This design is composed of six individual faceplates (three of each type) which are then assembled, along with the internal parts, to form the active cell. The inclusion of these joints, along with the mechanically operated locking pins may limit their use to *in vacuo* (FIGs **3,4**).

Each of the active and passive faceplates has the same kind of edge treatment, consisting of a finger joint and other standardized features. As the joint surfaces are parallel to the cube faces, the faceplates can be assembled in any order. A pin introduced at one end of the formed edge joint holds the two faceplates together. The pins are always inserted through a hole in an active faceplate. Because of the layout of the conductors on the passive faceplate, a standard 'XY' orientation of the assembled faceplates has to be adhered to. There are of course alternative conductor arrangements that avoid this restriction.

In addition to simplifying the manufacture, this physically allows a modicum of self repair (remove and replace), in the case of a radiation damaged space probe, for example [2, 9, 12].

(3) Drive systems

It is possible to use rotating motors, gears, racks and pinions on the faces, and so forth to drive an XY cube. The T-posts on the active faceplate might house the drive pinions and their associated bearings. The toothed racks are then incorporated on the channel surfaces of the passive faceplate. These pinions might also serve as rolling electrical contacts. The pinions are driven by an internal gear train, clutches , and motors. These would not be able to function in a contaminated environment of any sort.

There are several alternative linear electric motor types of interest for the mesoscopic active cell. One is a linear version of the electrostatic motor presented in [1], Section 11.7. The tunneling contacts and variable work function surfaces would be on the faces of the active T-posts, with the conductors embedded in the channels of the passive faceplate.

Another possible alternative is the "Electret Drive" mentioned below. The feasibility of incorporating a bound polarization in a mechanosynthetic structure seems questionable.

This study, however, focuses on the "Dielectric Drive". In general, when a piece of dielectric material is in a region of non-uniform electric field, it will experience a net force in the direction of increasing field strength [7]. Consider two parallel, charged conductive plates as in a capacitor. If a slab of dielectric material, thin enough to fit in the gap between the plates, is introduced at one edge of the plates, it will experience a force tending to draw it into the gap. Taking the displacement derivative of a continuum model energy balance yields:

Force=.5*epsilon*(chi)(a/d)(V^2)

where 'a' is the width of the plates and the slab, 'd' is the plate separation, 'V' is the imposed voltage across the plates, 'epsilon' is the vacuum permittivity, and 'chi' is the electric susceptibility of the slab material [13]. This simple model does not account for the non-colinearity of the electric field at the sides of the plates that are parallel to the slab displacement, and is therefore overly optimistic.

For this particular design, with a plate separation of four nanometers, and the width 'a' varying from 45 nm to 3*45 nm, the available force varies from 2*10^-10 N to 6*10^-10 N at one volt applied. This may not seem adequate, but assuming a nominal density of 2000 kg/m^3 for the active cell yields an acceleration of about two million gravities, neglecting damping. Overshoot and ringing appears to be more of an issue than the magnitude of the motive force.

When the dielectric slab reaches the far edge of a charged plate, no further motive force is available. It is then necessary to switch to another set of plates further along the path of motion. This is not unlike the switching in an ordinary forced-commutation electromagnetic motor. One difference is that this only provides an attractive force, unless the dielectric has a "frozen in" polarization, as with an electret. This case will not be considered here (FIG **5**).

To implement this drive system, the undersides of each of the nine male T-posts are divided into several conductive regions, separated by insulating gaps (FIG **6**). Only some of these "plates" are actively involved in moving the cell in the X or Y directions respectively. The "channel surface" of the active faceplate contains the ground planes, which together with the conducting plates embedded in the undersides of the T-post shelves forms the powered portion of the dielectric drive system. The passive faceplate is a solid piece of dielectric material (diamondoid), with interfacing conductors embedded in its channel surface.

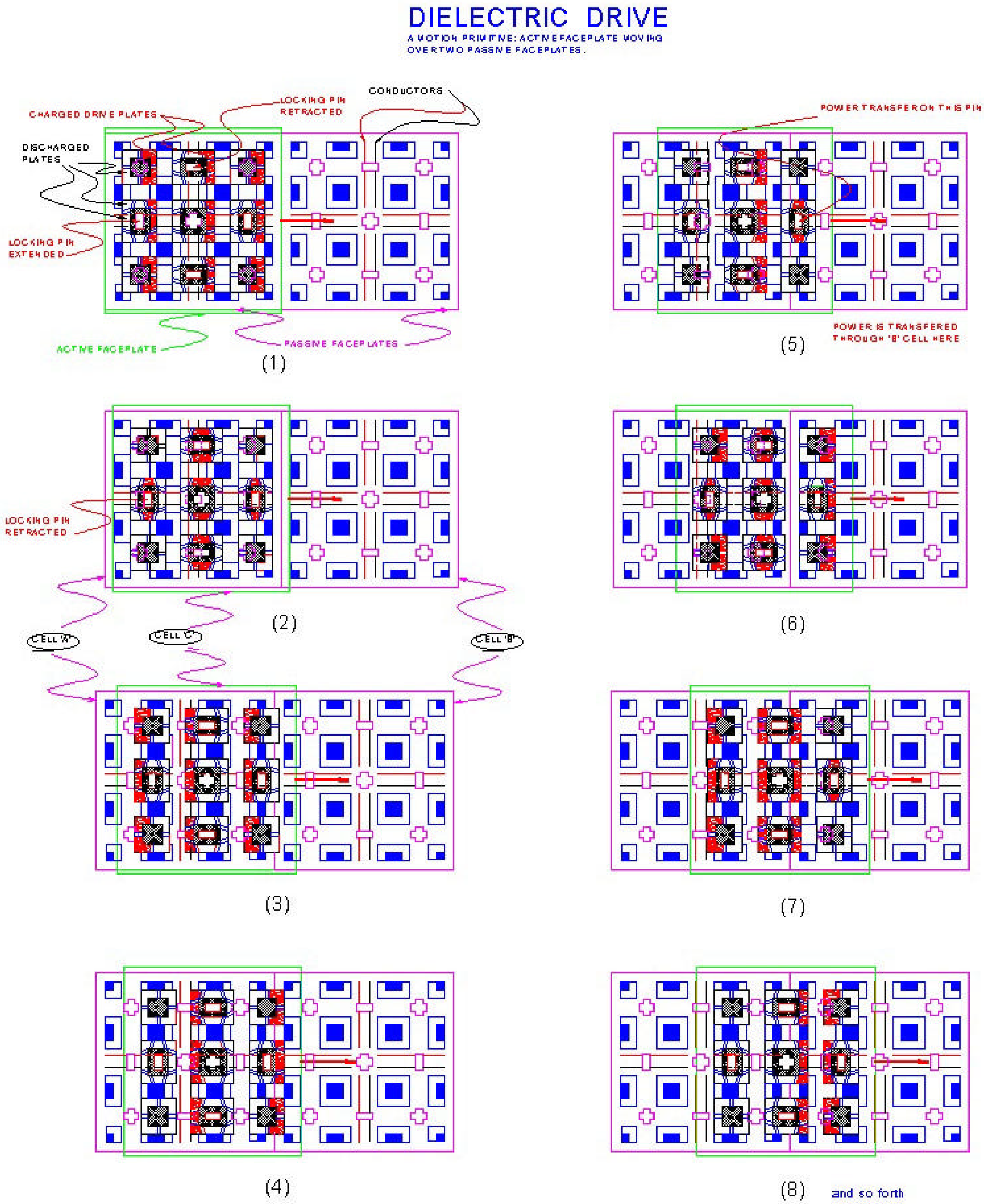

Figure (5)

The aspect ratio of these capacitors is very low, owing to design constraints. A significant part of the transverse electric field is therefore in the "fringing field" region, which is one reason the ground plane is extensive. Note also the "hot" plates extend into the volume of the T-post, as might some portions of the ground plane, which moves the transverse fringing field away from the dielectric slab. Additionally, the hot plates that span the channel between two dielectric shelves may be charged to assist in confining the drive field. With these features considered, the first order model looks a little better.

As this is a three dimensional, non-uniform electrostatic field on a scale where the susceptibility tensor may not be valid, a quality analysis will require non-trivial computer modeling [1, 5-8]. In addition, it may be necessary to account for the susceptibility and conductivity (for the time dependent case) of the conductors themselves. A bound continuum representation may provide a second order approximation [1].

A variant on this motor uses several interleaving layers of plates and dielectrics. This reduces the fringing field losses, as well as increasing the available driving force, at the expense of several additional complications.

Each active T-post has several internal leads, one from each conductive plate, to a set of electromechanical rolling contact switches on the interior side of the faceplate. These switches are operated by the rod logic controller when moving the active cell. In this design, the plates are neutralized by grounding, a dissipative procedure. An intriguing variation might use an adaptation of the reversible logic switch for this operation [14]. Note that the cell being moved relative to the power supply isn't necessarily the one providing the motive power. For this and other reasons, it is highly desirable to utilize sliding electrical contacts in this design. This is another area where more research is needed to proof a reliable design.

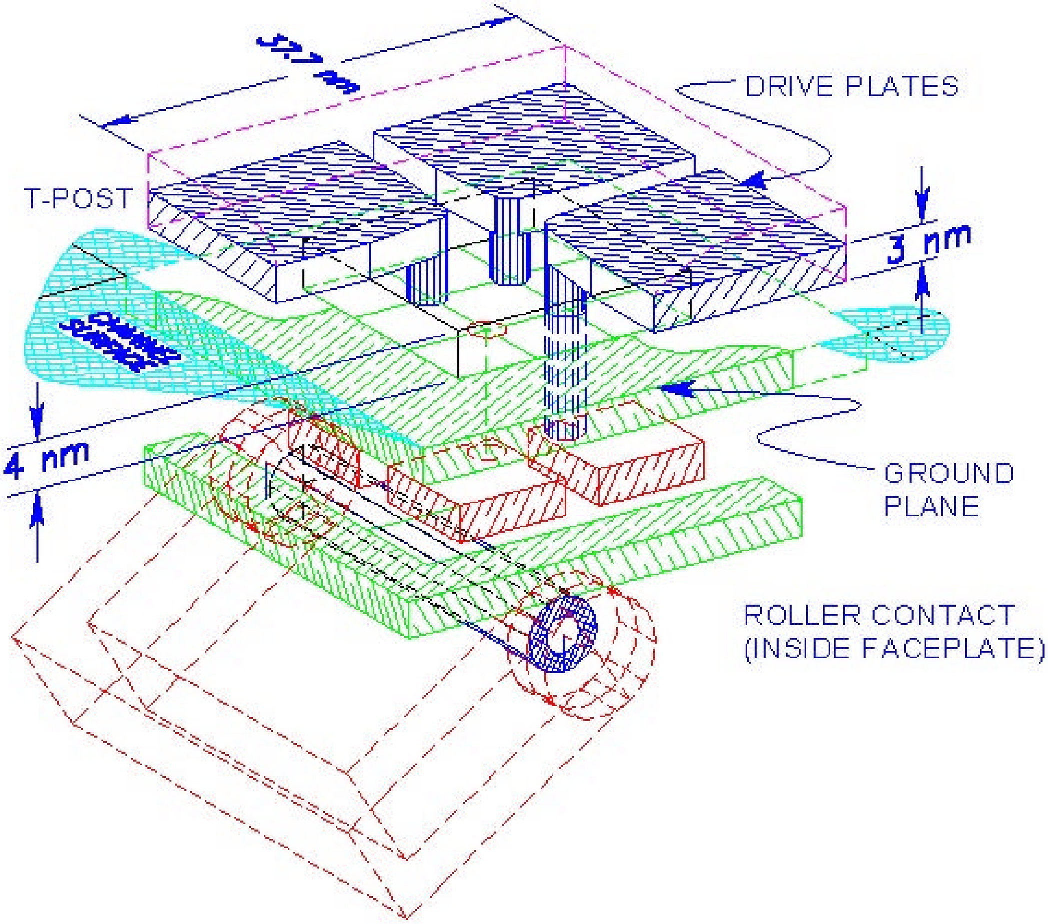

Figure (6)

The operating voltage range for the dielectric motor is quite variable, from greater than zero, to some prudent value below the dielectric strength of the specified 3nm diamondoid insulating gap. The desired motive force also has to trade off against tunneling losses, and the resulting heat load, due to the close spacing of the drive plates and other conductors.

In order to operate the drive system successfully, the motor controller needs a position feedback signal. This may be as simple as mechanical contact switches, perhaps incorporated in the locking pins, or by measuring the current to the hot plate, which, given a constant voltage, will exist for as long as the plate is in motion but not completely inserted into the charged plate. If the plate is charged, then disconnected from the power supply, the applied voltage drops as the dielectric is inserted, and then levels off when the slab is fully inserted. These methods are complicated by the tunneling and resistive losses.

Band alignment scattering is apparently a major loss mechanism in flat, sliding, eutactic structures [1]. This can be minimized by orienting the crystal structure of an active faceplate at 45 degrees to the structure of the passive faceplate. It should be noted that the induced polarization of the dielectric will draw it toward one or the other conductive plates, i.e. in the plus or (generally) minus Z directions, which then increases the sliding friction at that interface. This detrimental effect only occurs with the plates that are currently charged, although the entire faceplate is stiff enough to be involved in the 'Z' displacement. The unpowered contacting surfaces provide the overlap repulsive force to counter this effect.

(4) Interfacing (power and signal)

The four locking pins also serve as the cell-to-cell electrical contacts when they are extended into their matching holes. They are spring-loaded so as to be extended when no power is applied (i.e. "deadman" switches). A lever from the rod logic engine operates the pins. Two of these pins form the sliding contacts when they are in their partially retracted position. The other two are not in use when the cell is moving.

A fifth pin at the center of the active faceplate is for a more direct and lower resistance power transmission path. More such pins and holes can be added if a finer step resolution or greater shear strength is needed. Note that the dielectric drive is capable of stopping in many places, depending on the layout of the conductive plates.

The power and signal interface switch is located at the center of the cell. A set of power and signal busbars from each face terminate in a mechanically operated, conductive sleeve that can be extended to contact a conducting "routing" cube. This switch is an alternate location for the voltage boosters. An insulating framework holds the busbars, operating levers, and central routing cube in place. Any combination of sleeves can be extended, thus power can be shunted from any face, to any of the five other faces. Alternatives include rollers, moveable wedges or hinged members instead of the sliding contacts. Although this may seem crude, the intent is workability rather than refinement. A more sophisticated model might use strictly electronic switching here.

The busbars to the three active faceplates are routed directly to the external electrical contacts. Power is tapped off of them when needed to run the drive system.

The three adjoining passive faceplates contain flying capacitor voltage multipliers, also mechanically operated. The busbars from the interface switch are routed to these voltage boosters, and from them to the external contacts. The power and signals are always propagated in one direction (global internal coordinates x, y, z) at a time, and so can always pass through a booster with each cell-to-cell transfer. The amount of boost required is a function of several variables, both of design and of operation (a provision to rout around the booster whenever possible would be desirable). In this manner, the voltage is maintained at a nominal level over an extended aggregate despite resistive losses

A serial signal bus may be implemented by modulating the power, but the voltage boosters add some complications to this. An alternative is a separate line for signal (not considered here). Another alternative is acoustic transmission via the locking pins. These pins should include contact "switches", levers actually, to verify the locked and unlocked conditions. These same levers could be operated directly by the logic engine for serial signaling.

(5) Embedded Microcontroller (rod logic engine)

There are about 2*10^6 nm^3 of interior volume in this design.

A minimal controller might use about 10000 logic elements, occupying a volume of 10^5 nm^3. Another 10^5 nm^3 is allowed for a data storage system [1]. The logic engine and data storage modules can be mounted on the interior surface of one or more of the faceplates. The 10000 element logic engine is a minimal specification; there's plenty of room for more.

A rotary electrostatic motor occupying about 2*10^5 nm^3 may provide the mechanical power for this engine, as described in [1]. The materials of the dees may be chosen to have a lesser work function difference, to allow a lower working voltage. For packaging, it is desirable to use one of the passive faceplate busbars as a shaft mount for this machine (FIG **2**). Pinion gears or crankshafts on the inboard side of the motor provide the mechanical power transmission. It may be possible to use the stored rotational energy in the rotor to provide temporary power to other cells executing a "motion macro". The rotor would be mounted on a spline shaft, which allows it to move into a region where the work function surfaces are reversed. It then would function as a generator for a short while as it spools down, with the appropriate switching.

(6) An example maneuver: Motion Primitive

A "Motion Primitive" is defined here as a single cell move of one cell length in an allowed manner, or a connected group of cells moving by one cell length. The cell(s) begins and ends in the aligned rest position.

There are two different cases of interest here, owing to the chirality of the aggregate. In one case, a cell with an active face is moved by one cell length from a rest position on one passive face, to a rest position on an adjacent passive face. The passive-faced cells are assumed at rest with respect to the power supply and central controller (if there is one). In the other case it is a passive face moving across two active faces which are at rest. In general, there can be "fixed" cells connected to the three other sides of the moving cell that are parallel to the desired displacement. This won't be considered in the following analysis, which is simply to look at what is minimally involved in moving a cell.

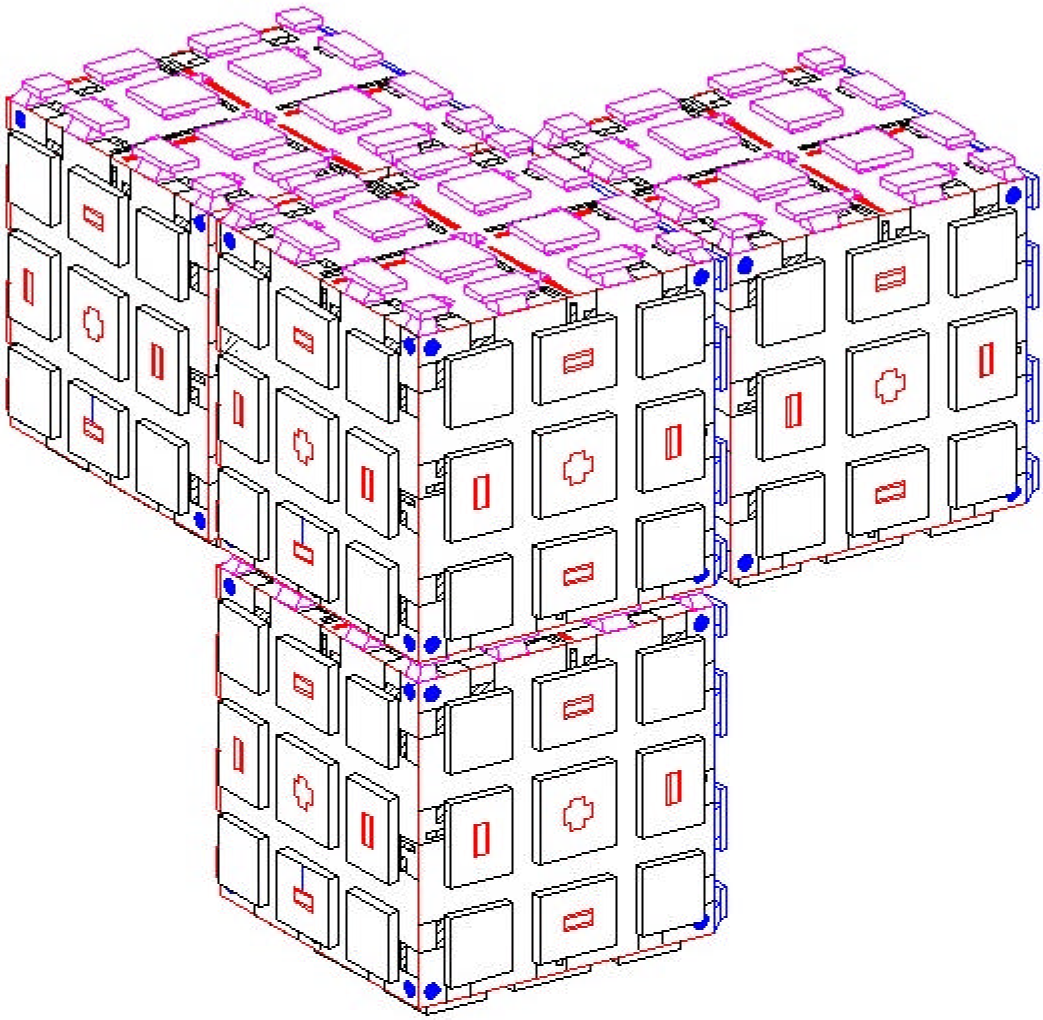

Figure (7)

In the first case, the cell (or connected group of cells) to be moved might be interrogated to establish handshaking and verify its functionality. Instructions are sent (in this simple case) to the active-faced cell to move over by one cell. The moving cell is providing the motive force, which requires (in this design there is no dedicated onboard energy storage) receiving power from the fixed passive face via two of its retracting pins. To move, the two pins not involved in energy transfer are fully retracted. The first set of drive plates is charged, and then the two contacting pins are withdrawn in a controlled fashion. It is necessary for the cell to begin its displacement before these two pins are completely withdrawn from the holes in the passive faceplate to prevent jamming the cell. Note that this is not strictly necessary if there are fixed cells on either side of the moving cell.

When the moving cell determines, via its position feedback system, that it has moved as far as possible with its first set of drive plates, it then applies power to the next applicable set, and grounds the first set. This procedure can be accomplished in two steps: first the "old" and "new" hot plates are connected in parallel. They reach a voltage midway between ground and the working voltage. This connection is broken, the old plates are grounded, and the new plates are connected to the main supply. This saves a portion of the energy stored in these capacitors.

This procedure is then repeated as the cell moves toward its new rest position.
When a spring-loaded locking pin/contact reaches an undesired receiver, it has to be actively prevented from dropping. The layout of the conductors is such that one pin is always in contact with the interface conductors on one of the two involved passive faceplates.

As the cell approaches the aligned rest position, the tapered locking pins will drop into their receivers. There is a position where no power is being delivered to the moving cell, as the pins are dropping. This does not seem to be a problem, as there is energy stored in the drive system, the voltage boosters, and in the rotating armature of the logic engine's motor.

In the second case, two active-faced cells are moving a passive-faced cell, which does not have to do anything. This is used to advantage in [9].

(7) Applications

a) Research Facility

The ability to manipulate several very small objects in three dimensions is very limited at present. It may be possible to build active cells with current silicon micromachining techniques, perhaps combined with some "bottom up" components. These could be very useful in studying the behavior of materials at the mesoscopic scale. Any face of a cell can be replaced with some other tool besides the standard faceplate. Incorporating microstepping can further increase the spatial resolution of the aggregate. It may be possible to use these microtech cells to construct an even smaller family of active cells [2]. A very interesting variant here would use larger active faceplates, connected to an external computer, to manipulate smaller passive faceplates not burdened with onboard microtech processors. The nanotech active cells hold their own potential.

b) Shape Shifter (Active Mesostructure)

An object composed of active cells and other specialty cells can change its shape and surface composition to form a very large number of different items. The Shape Shifter is described in more detail in [2].

c) Space Probes

A Shape Shifter makes for a very interesting space probe. The ability to act as the structural material of the probe's various instruments and propulsion systems decreases the amount of mass required. There is also a possibility of inflight self-repair of the active cells [2, 9, 12].

d) Drexler Universal Assembler.

It should be possible to use the standard active cell as a mounting platform for a nanomanipulator, or robot arm. The active cell aggregate provides the gross positioning in three dimensions, while the manipulator provides the fine control. The interfacing is already built in for the robot arm. The aggregate can also transport materials and hold large workpieces, forming literally a bridge between operating on the macroscopic and mesoscopic scales. This idea is explored in more depth in [9]

(8) Conclusion

As this is largely an exercise in theoretical engineering, there are more questions here than answers. Aside from actually building a nanotechnology active cell, issues of materials, sliding friction, sliding contacts, and so forth remain unresolved. This author would encourage those more qualified in the relevant fields to investigate the feasibility and the potential of an active cell aggregate.

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Glossary

Aggregate: A fixed number of standard active cells connected together by their mutual interfaces.

Cell Metric: a) The nominal lengths, edge angles, and face angles of the smallest cell of a particular system. b) The nominal edge length of a cell.

Group: A subset of an aggregate.

Motion Macro: A method of moving a group or groups of cells in an aggregate. (Called "Mode of Motion" in [(2]) Inspired by Jeffrey Soreff.

Standard Interface, Standard Face: The mechanical, power, and signal interfaces on a particular surface of a standardized active cell.