December 7,1995

The Construction and Utilization of Space Filling Polyhedra for Active Mesostructures

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1. Introduction.

An "Active Mesostructure" is a collection of mesoscopic, similar machines, built by nanotechnology methods (1). "Active" means each machine has the capacity to exchange power and signals with the other machines, and to interact with the external environment. An example of this is J. Storrs Hall's "Utility Fog" (2). This paper concerns another type of system, discussed in (3) and developed independently by this author. These machines are generally envisioned as cubes, though other types are entertained.

This is a system composed of identical, connected, space filling polyhedra (cells), each capable of moving with respect to its adjoining neighbors, singly or in groups. The cells are connected face-to-face. The scale of the cells (the "cell metric") is assumed to be on the order of 100 nanometers (mesoscopic), though much of the discussion would apply to cells of any metric. The simplest to conceive and design for are the parallelepipeds, specifically the cube. This is the example used for the purpose of illustration. Much of this discussion would also apply to non-cubical cells, of which the square plate (a "cut down" cube) is of interest for reasons of manufactureability. Some aspects of this discussion are specific to the cube and to its permitted degrees of freedom.

This article touches on methods of modeling, constructing, and programming a structure composed of many such cells. A general solution for transforming a large aggregate of cells from one arbitrary configuration to another is outlined. A few examples of applications and unusual devices are given. As we are speaking here of a machine that can radically alter its shape and surface composition, most applications haven't even been dreamed of.
The "Terminator T-1000" from the movie "Terminator 2" (4) is used to illustrate some of the concepts. The T-1000 machine is a somewhat reasonable depiction of a nanotechnological, mesoscopic version of the system outlined below.

2. General Description.

There are several geometries of interest for a space filling cell. Besides the cube, the hexagonal prisms and the slant parallelepipeds are capable of making the necessary face-to-face joining. These forms may be of interest when specific crystalline materials are desired for application or manufacturing reasons.

A distinction is drawn in the method of interfacing the cells between cells that can only slide apart, and cells that can either slide or simply detach from one another.

A right regular hexagonal prism is of interest from a manufacturing standpoint, as some single crystals form this shape naturally (i.e. they self-assemble). The resulting aggregate is constrained to movement perpendicular to the hexagon plane, which is useful in some products. A hexagonal prism with a width comparable to a cubical cell metric, and having standard interfaces at one or both ends, can also serve as a structural element in an otherwise cubical system.

There are two variations on the cubical theme of particular interest. The first is a cube with mechanical interfaces on each of the six faces, that are capable of sliding two connected cubes in one of the two directions parallel to the joined faces, and parallel to the edges of those faces. 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. These are "XY cubes" (**figure 1)**

The second type of cube has the same specifications as an XY cube, but with the additional capability to detach faces normally (3). These are "XYZ cubes". This distinction leads to a number of differences in how the cell can move in an aggregate, as well as differences in manufacture. In neither case do the cubes rotate in any way with respect to one another.

The XY cube requires a maximum of two extra moves to uncouple two faces normally as do XYZ cubes. The first move is to slide {the cube to be detached from} sideways, at which point the desired cube is free to move. The second extra move is to slide {the cube that was detached from} back to its original position. This can be seen by tracing the trajectories in the five cube configuration space, for examp le (**figure 4**.). This adds complications in various situations (see Extraction under Modes of Motion).

In either case, the standard cube (active cell) has, in addition to the mechanical interfaces, methods of receiving and transmitting power and signals from any face, to any face, along with the necessary interfaces for this on each face. Power and signals may be electrical, chemical, mechanical, acoustic, electromagnetic radiation, etc. Drive mechanisms on each face are required to move the cells. Cells in motion with respect to the power supply need to be able to continue receiving power in order to carry out some of the maneuvers listed below. This is accomplished with sliding contacts for the electrically powered type. Each active cell should have some onboard digital processing capability.

When the cells are aligned, they can be locked into position by the equivalent of a sliding pin in one cell engaging a hole in the other. A nanotech version may use something more subtle than this, like twisting the sliders or effecting a reversible electrochemical reaction.

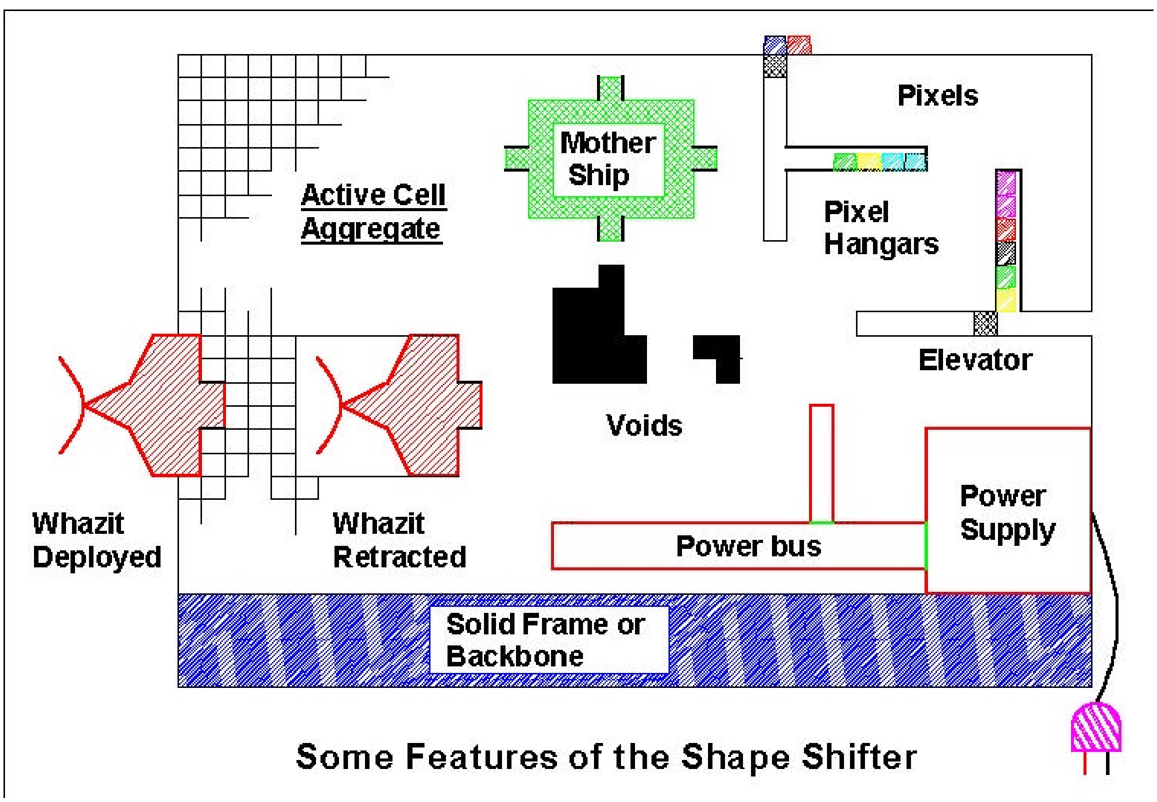


Figure 2.

Construction Methods.

The desired material for a nanotech cell structure is of course diamondoid (5), but other interim options should be entertained. Silicon chip and microstructure fabrication is currently the most mature transitional technology. It might be feasible to build active XY cells with a few extensions of these techniques (This technology is also mentioned in (3)). XY cells are mechanically simpler than XYZ cells, as well as having an inherently stronger cell-to-cell joint.

One idea is to fab the individual faces using ordinary photolithography processes. A silicon wafer is bonded to a removable substrate. Undercuts (T-slots) are made for the XY mechanical joints. Pinion racks are cut into the faces, to be engaged by a pinion on the facing cell. Through-holes are made to the substrate. Dovetails are side cut on the edges. A 3D template, or chaser, can be run over these various cuts to true them up. Perhaps diamond film is deposited. Conductors are masked and deposited.

The wafer is give a new, removable substrate on top. This is either made of active cells of the same design, or a cut template that can be slid onto the wafer from the side as a cell would do. The bottom substrate is removed, and various cuts made for mounting motors, gears, locking pins and drivers, and a microprocessor with the interface switch. More conductors and bonding pads are added. The individual faces are now removed from the substrate. This is easy if other active cells of the same metric are used here. The internal parts are made in separate processes that are already extant. The cubes are assembled using active cells (the first ones obviously aren't).

This produces cells on the order of a 1mm, or perhaps .1mm, metric, a far cry from 100nm. The size limiting factor seems to be the microcontroller die size. These would be very expensive, but useful.

Another similar technique is to make the entire body of silicon, hollowed out with five faces built in. This may be a square plate, instead of a cube. The innards are added and the sixth face is put on as a lid..

In order to make trillions of active nanotech cells, some sort of replication is needed. As these are not inherently self-replicating (except as Von Neumann's robot in a warehouse of its parts), it is therefore necessary to replicate the factories that make them. A proposed means of doing this is in (1). Perhaps the two methods can be combined.

Power can be either from an external supply, or a special module(s) with standard interfaces. Corridors of various integer multiples of the cell metric can be formed to transmit electromagnetic energy from one part of an extended structure to another. These waveguides can be for either RF or optical wavelengths. Existing quantum well laser arrays can be incorporated on a cell face for transmission.

Energy might be stored in chemicals, batteries, capacitors, superconducting ring waveguides or wires, strain energy, mesoscopic flywheels, and so forth.

Waste heat removal has many options as well, including scaled down versions of existing cooling methods.

Keeping the interfaces clean is critical to the operation of a mesoscopic active cell. One of the advantages of using XY cells is their natural tendency to wipe the interfaces clear of foreign matter when they move (see Square Wheels). This action can be enhanced by some sort of flexible shields at the edges of the cell. In addition, XY cells avoid the problem XYZ cells have of entrapping debris during a normal attachment.

Specialty Cells (pixels). (**See Fig. 1.)**

There is a need for special purpose cells, where one or more faces aren't standard, and therefore not able to interface. Special surfaces can include optical effects, chemistry labs, environmental surfaces, sensors, tools, and so forth. These units may have a volume of several standard cells. In any case, they will require extra attention (see Extraction under Modes of Motion).

Hangars and other multi-cellular structures

In order to store pixels and structural members when they aren't in use, a hangar of some kind is needed. This can be simply a box made of standard cells, or a special purpose cavity based on the same cell metric and the same standard interfaces. A special hangar would save on system resources, increasing structural integrity at the expense of internal mobility. Because the cubes cannot change their relative attitude, pixels are designed for each one of the (six) possible orientations In addition there can be edge (eight kinds) and corner (eight kinds) pixels, if required. This means a pixel hangar has to have racks facing in several directions to accommodate the various types of pixels, or that several differently oriented hangars are used.

Supercomputers for "master" control can be contained in a larger structure. These "mother ships" roam the interior and coordinate large groups of cells.

Structural cores, exoshells.

It isn't always necessary for the entire structure to be composed of active cells. There can be other, extended elements (again based on the same cell metric) incorporated for more specific applications. The active cells might only be a small percentage of the total mass (or volume). These extended structures can be backbones, frameworks, exoshells, and so forth. Active cells can also form the interface between these larger structures.

3. Figure games

For a given number of connected cells (an aggregate), there is a finite number of possible configurations. This set is referred to here as configuration space. For any give initial configuration [A], there are one or more possible paths to transform the cell aggregate into a final configuration [B]. This is the [A]->[B] problem. Note that different orientations of the same configuration are treated as separate entities. This is because the aggregate is assumed to be operating in the real world, where this matters.

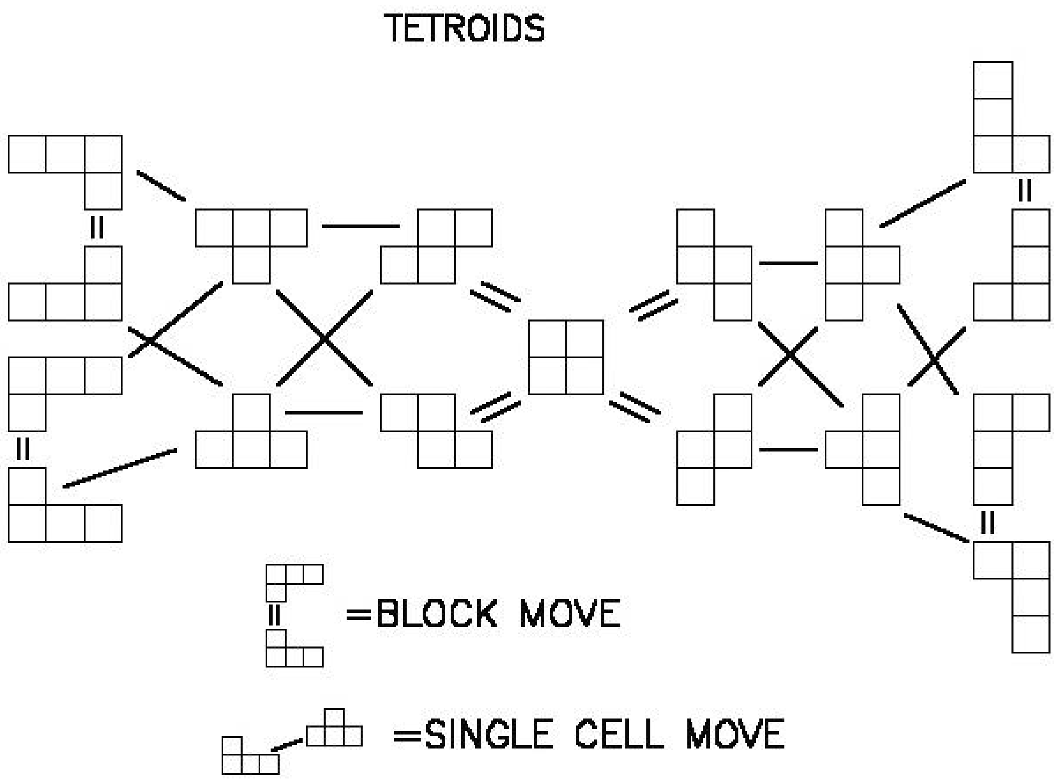
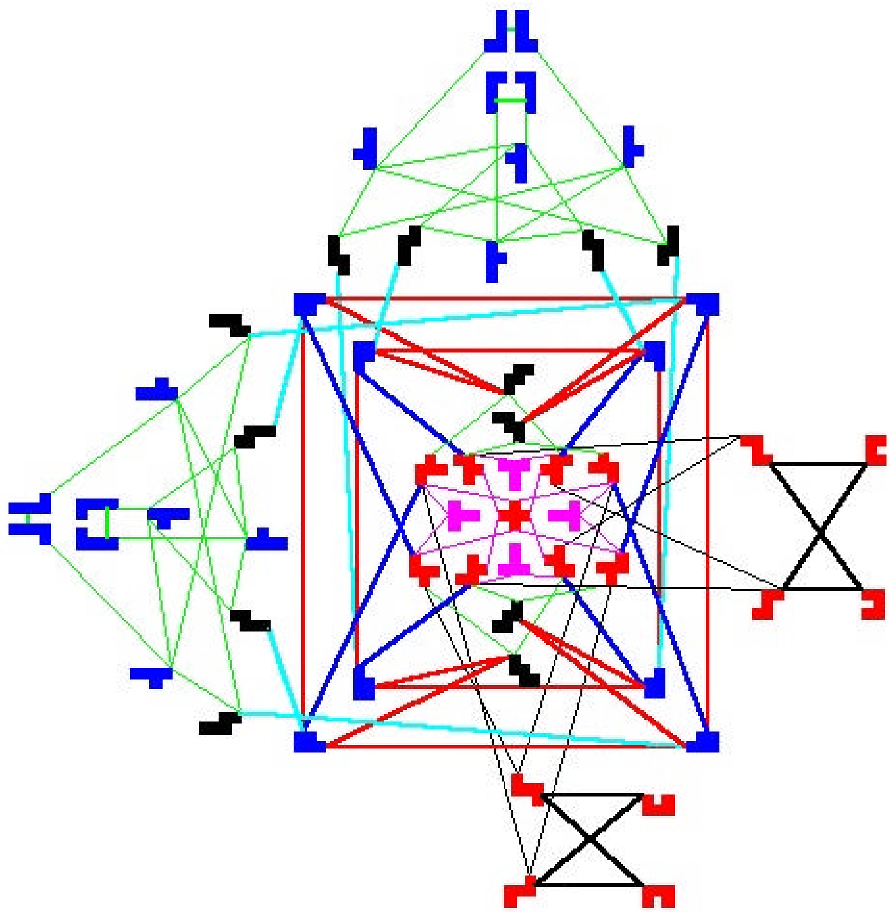


Figure 3.

These paths are trajectories in the configuration space, or figure games **(Figures 3.& 4.).** The line connecting one figure to another is a "motion primitive", consisting of a single cell move (light lines) or a single block move (heavier lines). So then, a connected sequence of motion primitives forms a figure game.

As can be seen from **figure (4.),** there can be many possible figure games to get from [A] to [B], but only a small subset of these are minimal. It's my guess that at between 100 and 200 cells in an aggregate, the total number of possible figure games exceeds the number of possible chess games.

This type of analysis is therefore intractable for even small numbers of cells. It can however provide some insight and guidance into partial solutions to the general problem. For example, in figure (3.) there is one configuration that separate the space into two distinct regions. To get from one side to the other requires passing through this gateway or terminus. It would simplify the master software to establish artificial termini, or rest configurations, which the cell aggregate has to pass through Although this may cause certain configurations to no longer be attainable, it also decreases the permissible number of figure games.



5 cube 2D Configuration

Figure 3

These configuration space diagrams can also be of use in discerning rules for generating minimal figure games. As a simple example, fivecube shows that to move from squarelike to rodlike, the block move should be made first. This principle may be extensible to the general case, and is used implicitly below.

If these solvable configuration diagrams are applied to the entire aggregate, a constrained general solution of [A]->[B] might proceed as follows: (this is [A]->[X]->[B])

1) Use the figure games for 8 cells (this is a solvable set) to assemble 2x2x2 cubes, then 4x4x4 cubes, etc. (these are artificial termini, or composite cells). This requires an addition choosing algorithm to decide which

cells should go to which composite cell. The issue should be computable at the current local level. Cells that are already in larger composites do not participate until the process reaches the scale of their composite cell.

In addition, there is the connectivity problem: which surfaces of which composite cells should mate? I think this solves itself on the way up to [X], but there are extra moves {out of the 8 cell figure game and then back in to the same point} in order for XY composite cells to effect the joining. These extra moves often require sending a request down a line for a single row, slab, or block move.

Let the excess cells remain on exterior surfaces. Slab move or block move them as and when needed to finish other large cells. This requires a more global programming approach, but again at a level commensurate with the current operating scale.

2) At the point where this produces a solvable (meaning a complete set of figure games is available), arbitrary configuration of large composite cells ([X]), reconfigure the aggregate in the most [B]-like shape. This is done with a 3D pattern matching program. Slab or block move the remainder cells to enhance the [B]-ness (this is carried out at all applicable scales in turn also).

3) Again, use the figure games for 8 cells to refine the structure at smaller scales. At each scale, refer to the [B] configuration file to select configurations most like [B]s morphology at that scale. Connectivity of the composite cells is more computation intensive in this phase of the transformation, as [B] is not arbitrary.

This description doesn't include such details as larger embedded structures, internal voids, and pixels. These would require application specific software. There may be less brutish ways to determine trajectories than the figure game analysis given above, perhaps based on search algorithms and interaction rules.

In (4) there is a scene in which a {humanoid shape [A]} transforms into a {facsimile of the linoleum floor [B]} it's standing on. A transformation based on the above algorithm might look something like this: First, the pixels are retracted to their hangars. The smooth surfaces of [A] give way to a grainier, cubical geometry. The cubes merge to create larger cubes, repeating the process until a stack of cubes (say 40) resembling a blocky snowman is created (this is [X]). The master program compares {"flat plate on floor"} to the 3D configuration space of 40 cells, and deduces the best match to be a slab of 39 cubes with the 40th cube sitting on top. Using its map of the figure games, it now rearranges [X] into this configuration, following a minimal trajectory (this is the [B-like] shape). These 40 composite cells now disassemble into 160 composite cells arranged as 280 cubes in a slab with 40 cubes sitting on top. The process continues until the desired thickness is reached, then the remaining cubes on top are brought into the main slab, which is more like a film by now (this is [B]). Optical/environmental pixels are expressed on the top surface, and display a picture of a linoleum floor.

For the case of arranging cells that possess individual identities, there exists a general solution, extensible to n-dimensions (6). The puzzle in which 15 squares are in a 4x4 array with one empty cell can demonstrate this. As it is an energy intensive algorithm, its utility is limited, but useful in certain circumstances. More generally, these kinds of games can help develop rules and algorithms for dealing with large aggregates.

Another possible solution to [A]->[B] is the "free for all". This is more akin to cellular automata, in which each cell follows a few rules of interaction. The cells in [A] are sent their new [B] addresses, and then let loose. I'm not at all sure this would work, and even if it could, it would be very energy intensive.

4. Modes of Motion. (Figure 5.)

For engineering design, the above methods have limited utility. A more useful approach is to define certain types of group movement, preferably as distinct from one another as possible (Figure 4.). These tools then provide a descriptive language for the design engineer, as well as a simplification of the programming.

The modes of motion set presented below is not particularly orthogonal, and certainly not exhaustive. It is, I think, a step in the right direction.

XYZ only Modes

1) normal detachment (These are motion primitives as well.)

2) normal joining

XYZ and XY Modes

0) A single cell move.

1) Single row extrusion.
a) Internal: Two or more moving surfaces contact the aggregate.
b)External: only one surface of the row contacts the aggregate.
2) Block Move. A one, two, or three dimension group on an exterior surface. Note that Mode 1b) is a subset.
3) Slab Move. Like 2), except two or more moving surfaces in contact with the aggregate. Note Mode 1a) is a subset.

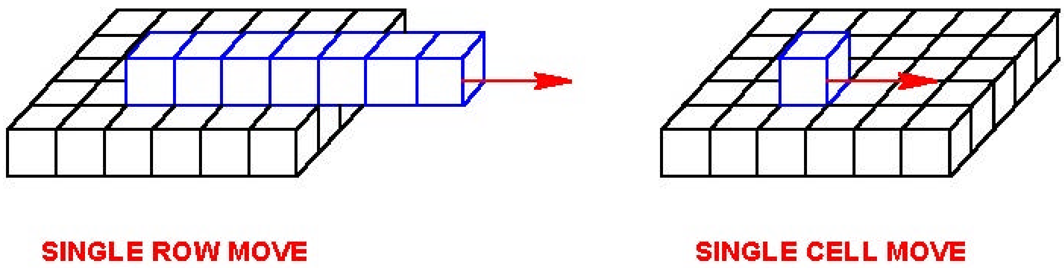


FIGURE (5A) MOTION MACROS (MODES OF MOTION)

Cascaded Modes.
By simultaneously making basic moves in a concatenated, or cascaded fashion, various unusual mechanisms can be built (see Dodging Bullets) and very high relative speeds attained (see Addendum: Space Probe Launcher).

4) Telescope.
5) Cascaded Block Move.
6) Cascaded Slab Move.

Methods of changing a group's members. All three of these are illustrated in the Red Cell Filter/Pump.

7) Deposition. Cells are sheared off in XY fashion, and left on a "fixed" part of the aggregate.
8) Acquisition. Cells are slid onto a "moving" group. Note this is the complement of 7), and the definition depends on what part is considered fixed.
9) Exchange. This move allows two separate structures to appear to pass through each other.

10) Coordinated Array Moves. All of the above modes can be carried out as simultaneous or sequenced array moves on an extended aggregate. Examples are Tank Treads, Systolic Pump, and density variations.
11) Move with Stop and Feed. Any of Modes (1-6), and 10) can be stopped so that additional cell can be added (or removed) before resuming the mode.
12) Extraction. This is a combination of several simpler modes and primitives, used to bring a pixel to an exterior surface (express a pixel). The generic pixel is assumed not to have a standard

interface on the face closest to the surface. The specific combination of moves is highly dependent on the type of cell. For an XYZ cell, a row detachment and slab move to form a corridor, followed by a single or double-cell extrusion, suffices. There are 24 possible slab moves that can form this corridor for the pixel- four to each face. Only the four slabs associated with the pixel face are useful here. When the pixel reaches the (presumably flat) surface, either an extra cell has to be present on the surface to receive it (only if it has side interfaces), or a second cell attached behind it forms an elevator and unloading dock. With the pixel(s) expressed, the rest of the procedure is reversed to restore the internal structure.

For an XY cell, no row detachment is possible. A single row extrusion is required, which has to turn and move across the surface until the pixel comes up. The array has to be kept out of the way of the single row. The pixels move across the surface, out of the way of the single row, and the row retracts. This would also work for XYZ cells, of course. This method imposes some interesting restrictions on how the array is constructed.

To return the pixels to their hangars, the procedure is simply run in reverse.

Example: Humanoid into linoleum floor.

By using these modes with some sort of expert system to determine what to do, the aforementioned [A]->[B] example might proceed roughly like this:

First retract the pixels. Use the 8-cell figure games as above to collect stray cells into some (small) composite cell size. Now the telescope mode is used on the vertical portion, and the cascaded block move for the horizontal. At the base of the blob, a transition is needed. This is done with stop-and-feed. The interior telescope sections move first, and form the first layer of blocks against the floor. Square Wheels are used to move across the floor. The next layers out form a cascaded block on top of the floor layer, and so forth. As the cascading blocks move away from the ex-humanoid, downward and crossways feeds are made to fill in the "cross" that would otherwise form. As things are settling down, pixels are expressed and display a picture of a linoleum floor. This method would appear much like the depiction in (4).

5. Devices.

Cube Pump. **(Figure 6.) (missing in this buikd)**

This was one of the first (1991) widgets the author devised. As the working cubes are moving around a lot, they're subject to premature wear. Perhaps special cells should be used here, or the working cubes can be time changed.

In operation, it is like a piston pump, with the cube performing as valves as well as pistons. The drawing shows a near minimal XY cube version, but in practice the bore and stroke can be varied independently to produce a pump with a 2x3 bore and a 50 cell metric stroke, for example.

This device could also operate as an internal combustion piston engine.

. Tank treads. **(Figure 7.) missing**

A synchronized array block move looks a lot like the treads on a military tank, and on some conveyor belts.

Systolic Pump **(Figure 8.)**

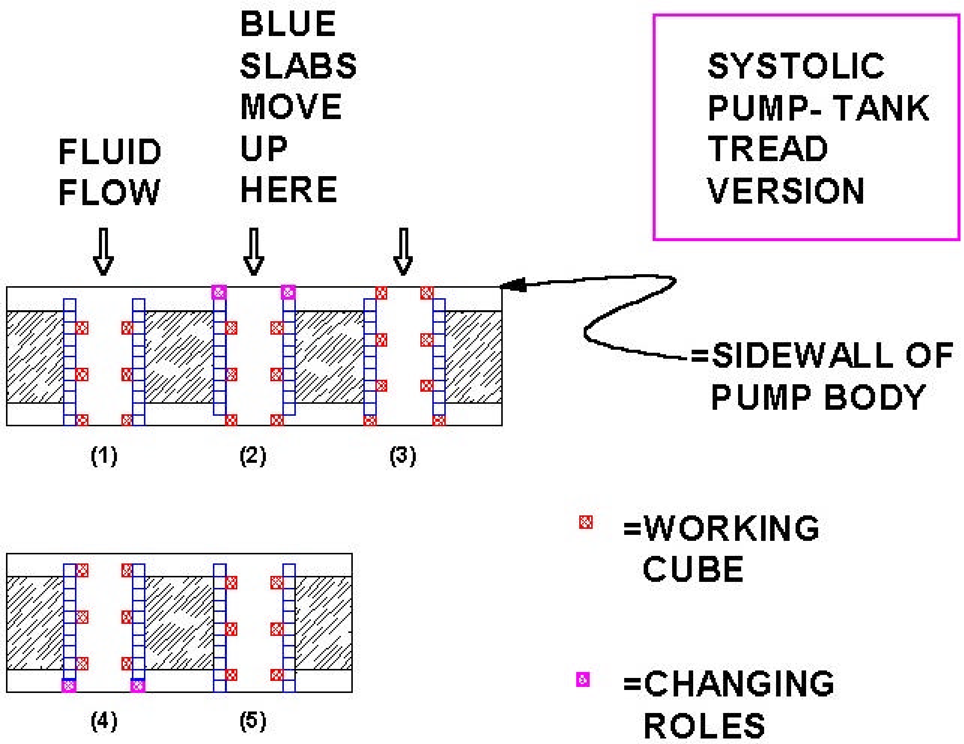


Figure 8.

By incorporating tank treads inside of a corridor, fluid can be entrained and moved in the manner of a systolic pump. Another method is to use out-of-phase cascaded slab moves.

Square Wheels. **(Figure 9.) (missing from this build)**

These are out-of-phase, synchronized slab and block moves with feeds. If it's actually being used as a wheel, one or more wiper cells can be added to help keep it clean.

Red Cell Pump. **(Figure 10.)**

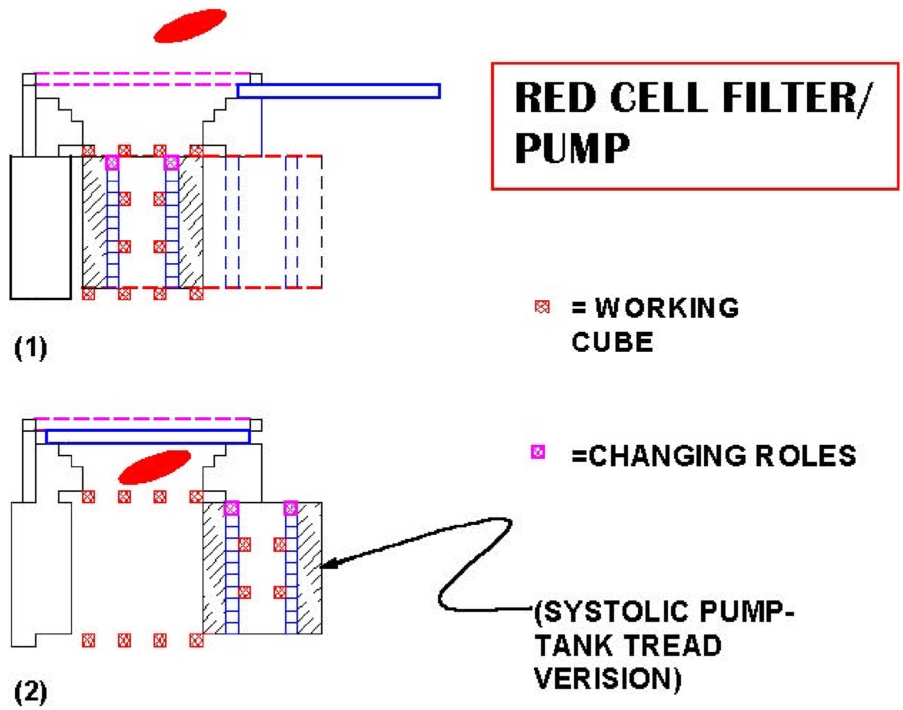


Figure 10A

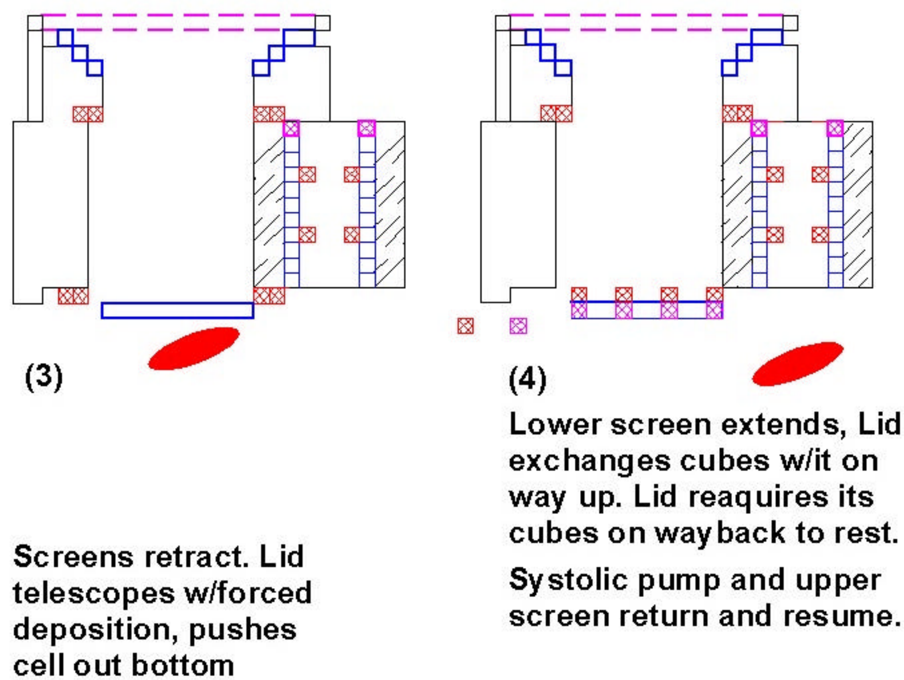


Figure 10B.

This was designed in response to T. Toth-Fejel's draft article. It demonstrates a lot of the basic modes and variations on them.

Space filling structures. Density variations.

By making array moves, a variety of unpacked structures can be formed.

Dodging Bullets.

For a military or space AMS (or a Terminator), it may be possible to detect and track incoming projectiles, and rearrange the internal structure to form a corridor for the objects to pass through.

A little calculation: Say a 1cm bullet traveling towards the AMS at 500 m/s. Say an onboard micro-array radar, 10m range, <1cm resolution (I think this device already exists). Add a 100 GigaFLOPS (why not?) DSP for extra comfort. The time in which the AMS has to react is then 10m-s/500m, or .02sec, less processing time at signal aquisition. The distance that the material has to move out of the calculated target zone is ~1cm for a 2cm square corridor. The required maximum average radial velocity is then 1cm/.02s, or 50cm/s! Note that most of the material doesn't need to move the full 1cm. In addition, consider that an AMS of this kind would probably operate at less than a fully packed density, for increased internal mobility, and that the modes of motion can be cascaded slab-on-slab, and I don't think this is such a far-fetched notion.

6. Conclusion. That's it. Bye bye!

Glossary

[A], etc.: A specific configuration of a given aggregate.
[A]->[B]: Change the shape of an aggregate from [A] to [B].
Active Cell: A standardized machine, capable of interfacing and interacting with identical units.
Active Mesostructure: A collection of interacting, mesoscopic machines (Ref. (1)).

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

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

Composite Cell: A group of cells that form a larger cell similar to the cell metric.

Configuration: An arrangement of the cells in an aggregate in which all cells are centered and aligned at the cell metric.

Configuration Space: All of the possible configurations of an aggregate. Motion primitives form the links between configurations. There are three types of mutually exclusive spaces comprising one, two, and three dimension aggregates.

Express (pixel): Remove a pixel from its hangar and move it to an exterior surface with its property face(s) facing out .

Figure Game: A permitted trajectory in configuration space, from one configuration to another. A set of linked motion primitives between two arbitrary configurations.

Figure Game Set: All possible figure games for a given aggregate size.

[A]->[B] Figure Game Set: For any two configurations, the set of all possible trajectories between them.

Fully Packed: No internal voids in the aggregate- all cell positions occupied.

Group: A subset of an aggregate.

Mesocell: An active cell of mesoscopic proportion, consisting of roughly 10^7 to 10^10 atoms.

Microcell: Bigger than a mesocell. Based on microtech rather than nanotech.

Microtech: Engineering objects on a scale of roughly .1 micron to 1mm. Many of the atoms are imprecisely positioned, compelling a high degree of structural redundancy.

Mode of Motion: A method of moving a group or groups of cells in an aggregate.

Motion Primitive: (a)A single cell move of one cell length in an allowed manner, or (b) a block or slab move of one cell length.

Pixel: A cell with one or more non-standard faces, used for surface property expression.

Point Probe: The leading spacecraft in a space probe convoy. It is a sacrificial mass for clearing a corridor in space of ambient particles.

Rest Position, Rest Configuration: The configuration an aggregate or a group might assume when it's not doing anything.

Standard Interface, Standard Face: The mechanical, power, and signal interfaces on a particular surface of a standardized active cell. Note that the interface is different for each different face orientation.

Terminus: A configuration that an aggregate, or part of an aggregate, has to assume (by necessity or by design) at some point in a figure game.

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Addendum

Space Probe Launcher:

The cascaded telescope mode might be used in a space based launch system. This study design launches one milligram (active mesocell aggregate) microprobes at 10 km/sec.

The launcher, when in its rest position, looks like a thinwall cylinder one meter long, 10cm diameter, and massing on the order of 100 grams (7). It is almost entirely made of nested, coaxial carbon Bucky tubes, able to slide longitudinally with respect to one another. Each tube, or stage, is composed of two or more nested and interlinked Bucky tube layers for various amounts of tensile strength, and for accommodation of circuitry and superconductors. Each stage can move at a maximum velocity of one meter per second with respect to its two nested neighbors. Each stage has superconducting, sliding electrical contacts to receive its power, and to transmit power to the tubes nested within it. There are 10000 nested stages. The microprobes are attached to the forward inner surface of the innermost stage, and have a total mass of one milligram (~10^10 mesocells). The outermost tube is fixed to the rest of the launch system.

The relative acceleration between any two stages is one meter/sec^2. The motive mechanism can be molecular-mechanical, linear electrostatic motors, wave-guided RF EM radiation, cascaded chemical reactions, etc. Friction losses have to be very low, as there is no way to absorb the heat.

Before launching the probes, the telescoping sections are extended rearward 5000 meters. To do this, each stage moves 50 cm with respect to its two adjacent stages. This is like pulling back a slingshot.

To effect a launch, all the stages are powered and accelerated simultaneously for one second. After a one second boost phase, the telescoped stages are back in the rest configuration. Each stage has moved 50 cm with respect to its neighbors, and is moving at the rated one meter per second per stage. The innermost stage is moving at 10000 meters per second relative to the outermost, fixed stage. At this time, the payloads are released, and the stages decelerate. The energy produced by deceleration is fed back to the fixed launcher as regenerative braking.

The stages are extremely thin walled tubes subject to tension loading on their long axes. It should be noted that 1) there are always at least two tubes nested during the boost phase, 2) the maximum load is on the outermost tube, which has the largest diameter, and the largest number of Bucky tube laminations (about 380). The first 475 stages have 2-lamination stages. Another lamination is added every 25 stages. The methods of linking and propelling the laminations in a stage may have to be coupled to distribute the tensile load over all of the laminations. In addition, it might be necessary to terminate the tube with annular diamondoid caps linking the laminations together.

Buckling:

It may be possible to internally pressurize the stages during the first part of the boost with waveguided RF EM momentum introduced at the forward end. The radiator would then have to move out of the way before the 10 km/sec stages reach it. A superconducting reflector capping the inner stage may be useful for this and for the prelaunch extension.

Wandering:

Any lateral departures from linearity during boost would quickly produce a mess. The launcher is most vulnerable to external perturbations when in the extended, prelaunch configuration. Any sideways motion has to be eliminated before boosting. One method is to extend and retract various stages out of phase with the induced "snaking". The acceleration profiles for different stages can also be actively varied to achieve the same effect during boost. An alternative is a guide wire or tube.

Power Dissipation:

Power required is about 10 megawatts for one second. The power distribution and energy conversion have to be nearly perfect, as there is essentially no available thermal mass to absorb losses. If any superconductor in the 100 gram launcher mass were to go over its critical temperature, for example, the launcher would explode. Regenerative braking is a requirement.

Construction:

The tubes are gigantic in comparison to today's Bucky tubes. In addition, the interlinking (which may reduce the strength of the carbon sheet), superconductors, and so forth, add extra complications not dealt with here. It could be that Bucky tubes are superconducting themselves, which may or may not be a good thing here. The superconductors may consist of 1-2-3 ceramics plated onto the carbon tubes. It might be feasible to build a carbon fiber version of lesser performance.

A slightly larger version of the study design (say 30 km/s), onboard an Earth satellite, could send microprobes to any point in the Solar System.

It has been evident for quite some time that the first workable star probes will be nanotech based machines massing less than one gram. This gizmo might be scaleable to speeds of interest (some decent fraction of c) to interstellar probe designers, at least for the initial boost (the probe's cells then rearrange to form a maser sail). A reasonable launch turnaround time is required, since point probes are sent first to bore a corridor in the interstellar medium, followed by the science probes.

Acknowledgments:

Jeffrey Soreff, for providing the right answers at the right time.

Tihamer Toth-Fejel, for encouraging me to write this up.