The Case for Advanced Electromagnetic Micro-Motors as the Currently Most-Practical Means of Developing Exponentially Self-Replicating Micro-Robotic Construction Systems for Mass-Producing Hybrid Micro-Nano Products

Abstract

The ongoing factory robotic revolution has yet to reach the micro-scale, in part due to over-fixation on integrated circuit manufacturing approaches to micro-mechanical systems (MEMS). In particular, high-performance micro-motors have been major {technical and economic} stumbling blocks. In this case, it makes sense to drastically scale down more conventional approaches (with suitable adjustments).

Once such technology is in hand, it opens the door to alternative micro-construction processes (given moderate product redesign to facilitate micro-assembly processes), including the development of micro-robotic micro-construction systems that can mass produce copies of themselves. (In this context, integrated circuit manufacturing processes would primarily be used to mass produce useful pre-fabbed {building blocks and templates}, rather than to produce finished networks of MEMS.)

Our initial micro-robotically-constructed target products include (1) sub-nanometer-precision {positioning and manipulator} systems that could also be used for atomic force microscopes (AFMs) and micro-optical microscopes (MOMs), (2) sub-nanometer-resolution micro-scanning-electron-microscopes (micro-nano-SEMs), (3) sub-nanometer-resolution micro-inert-ion microscopes (micro-nano-IIMs)}. In combination, these would be breakthrough instrumentation systems for {nanotech and biotech} research and development. There are some very-important micro-nano-level {scanning and fabrication} applications that would become feasible with affordable arrays of such systems.

Micro-robotic production systems for such products could consist of micro-robotic modules (MRMs) that could be arranged into micro-assembly-lines for producing micro-products. Of course MRMs are one of the most important end products that could be produced.

Conventional mass production technology is suitable for prototyping thousands (10^3) of MRMs, which could then self-replicate millions (10^6) of similar MRMs. Subsequently, MRMs could be used to {develop and produce} further-scaled-down micro-manufacturing-systems that could economically produce billions (10^9) of 2nd generation MRMs that could produce trillions (10^{12}) of end products (including still-smaller 3rd generation MRMs). And so on. The 2nd generation MRMs could integrally-incorporate capabilities for {hybrid nano-optical microscopy, atomic force microscopy, and multiple-nanotube-based manipulator fingers}.

The genesis of trillion-module MRM micro-nano-SEM systems would naturally revolutionize {molecular-level biotech, sub-10-nm nanoelectronic integrated circuit production, combinatorial chemistry, and custom micro-nano fabrication of macroscopic quantities of metamaterials}, and so on.

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1 Introduction

((IMPORTANT NOTE: one of the major upcoming revisions deals with means of using very low resistance {carbon nanotube bundle micro-wires or multilayer graphene ribbon micro-wires} instead of superconductors for the first generation of {micro-electromagnetic actuators and MRMs}.))

1.1 The Great Importance of Advanced Instrumentation

The early visions of nanotech are almost as old as the invention of integrated circuits — both developments date back to the late 1950s. Since then, the development of nanotech has been dramatically slower than the exponential "Moore's Law" progress in integrated circuits, primarily due to the lack of suitably-advanced instrumentation.

The development of micro-nano-SEMs is thus a hugely-important development that will see very widespread use. We aim to {piggyback on and capitalize on} this enormous opportunity.

For more micro-nano-SEM info, see:

- Generating a Revolution in Electron Microscopy

  (http://www.nfab.co.uk/)

- 'Microscope on a chip' to give four times the detail - tech - 13 June 2008 - New Scientist Tech

  (http://technology.newscientist.com/channel/tech/dn14136-microscope-on-a-chip-to-give-four-times-the-detail.html?feedId=online-news_rss20)

We also aim to use micro-nano-SEMs to develop the technically-challenging key components for next-generation CAPE-micro-nano-SEMs, based on coherent atomic-point emitters (CAPEs). This technology (which Biomed Solutions hold 4 patents on, plus 2 more filings underway) will facilitate even-lower levels of low-voltage operation, thus providing even-greater bio-compatible imaging capabilities. The very low operating voltage of CAPE-micro-nano-SEMs is compatible with extreme miniaturization, so they are also presently the leading prospect for ultimate nano-scale "nano-eyes".

((One of the many reasons that wildly-hyped bottom-up nano-assembler visions of nanotech never took off — even after nearly 30 years of relentless PR— is that such predominately Helen-Keller-like nano-systems basically involve "working in the dark". That's an extremely-severe practical handicap for such extremely-challenging technology development. In any case, once you do have affordable general-purpose atomic-resolution "nano-eyes", there are much better strategies to exploit them, as we shall see.))

1.2 The Great Importance of Economical Super-Mass-Producibility

The micro-replicating MRM modules are a means of mass producing vast numbers of miniature micro-nano-SEMs (since each module would include one). This is important for such applications as:

- Looking at billions of DNA base pairs or exhaustively inspecting all of the expressed proteins in a cell (and do so for lots of cells) requires huge numbers of "nano-eyes" working in parallel to get enough throughput for industrial-scale bio tech.
- Being cost-competitive for next generation nanolithography at world-class production levels. To successfully compete with an {already very large and already entrenched} technology requires being hugely-advantageous, not merely better. This requires massively parallel systems.
- Doing non-trivial bottom-up nanofabrication involving (for example) e-beam nano-welding of {carbon nanotubes, graphene, and other things} for making {advanced metamaterials or stuff for

solar power conversion} requires vast numbers of tiny inexpensive micro-nano-SEM arrays to affordably produce macroscopically-useful quantities of stuff.

- Providing the enormous atomic-resolution screening capacity needed for massively-parallel genetic-algorithm-guided combinatorial-chemistry searches for advanced {nano-particulate catalysts, super-enzymes, highly-specialized drugs, and many other very-high-value nanostructures}.

While there are many important much-less-ambitious applications, we want to concentrate on those that most-directly lead to much bigger {technical and economic} rewards. So it's important to consider some of these longer-term prospects up front.

1.3 Commercialization Considerations

1.4 Abbreviations and Technical Terms

Abbreviations:

- micro-nano-SEM = atomic-resolution micro-SEM. (100 eV to 300 eV range)
- CAPE-SEM = coherent atomic-point emitter micro-nano-SEM. (0.1 eV to 10 eV range)
- LTS = low-temperature superconductor (≤ ~ 1–20 °K)
- MEMS = micro-electro-mechanical systems MRM = superconducting micro-automata replicating technology.
- SEM = scanning electron microscope. (10 keV to 100 keV range)
- HTS = high-temperature superconductor (≥ ~ 10–20 °K)

Technical terms:

- Cryogenic temperatures or liquids are roughly those below -150 °C (123.15 °K).

2 Technical Background

2.1 Micro-SEMs

2.2 Artificial Replicating Systems

For comparison, common granulated table sugar crystals are about 0.5 mm.

3 Enhanced micro-nano-SEM Systems

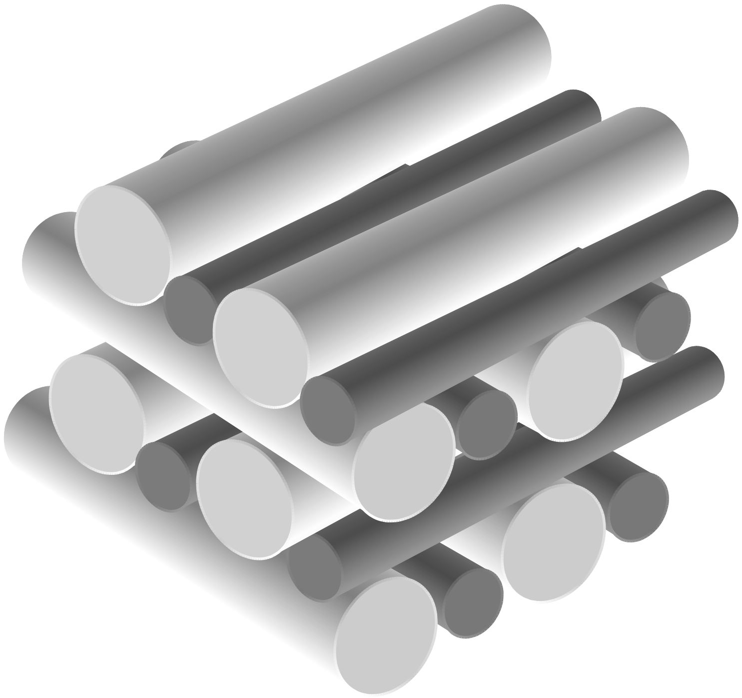
3.1 Hybrid Near-Field Nano-Optical Imaging

3.2 Imaging-Based Nano-Manipulation Systems

3.2.1 {Nanotube, fullerene, and graphene} {sorting, modification, and construction}

3.2.2 Video-feedback-based metamaterial fabrication.

Crossed planked-planes consisting of varying nanotube {types and diameters} can be used to provide precise spacing between nanotubes of different layers.



4 MRM Ultra-Mass-Production Systems

4.1 Artificial Self-Replicating Systems

In the 1950s, John von Neumann (with Stanislaw Ulam's input) initiated scientifically-serious consideration of artificial self-replicating systems (he called them "universal constructors") by outlining a constructive proof their feasibility in automata-theoretic contexts. (This proof was {completed and corrected} by Arthur Burks after von Neumann's untimely death.) Also in the 1950s, Edward F. Moore subsequently proposed actual technological realization in the form of artificial mechanistic plants.

Unfortunately, there are enormous practical {technology and economic} challenges involved in {designing and developing} such systems. So despite their enormously-powerful potential of practically-useful systems that could increase their numbers exponentially, there has been very little practical progress of the economically-significant kind.

((There are some rapid prototyping systems that can make many of their own parts, but there are presently no substantial {technical and economic} advantages for incorporating them into very-large-scale self-replicating systems. However this sort of technology might well eventually be practically-incorporated into other {economically and practically}-viable sorts of very-large-scale self-replicating systems.))

4.2 Advantages of Superconducting Micro-Automata Technology

5 A Baseline MRM Production-Prototyping System

5.1 Aim for Commercial {Utility and Spin-Offs} at each Stage

5.1.1 Simplify first, {optimize and enhance} later.

5.1.2 Selected {prefabricated materials and supplies} must be readily affordable.

5.1.3 Multi-module collaborative assembly (instead of one-on-one assembly).

Assembling a new module will initially be done by using a few modules (say 4) working together. For many assembly operations, this should be easier than one-on-one assembly.

5.2 Physical {Scaling and Staging} Considerations

There are many practical design issues that are easier to solve in a series of successively more challenging stages. The initial scale point-of-departure should not be too large to be marginally-relevant, nor too small to be easy to work with given available technology. Likewise, the steps taken from stage-to-stage should not be overly-ambitious (meaning counterproductively trouble-prone). In this program, each stage of development work provides {important experiential knowledge and important developments tools} needed for the next stage.

Here are the principal project technology target stages:

- Stage 1 — 10^3 $(1\ \mathrm{cm})^3$ modules, externally-assisted partial-self-assembly.
- Stage 2 — 10^6 $(1\ \mathrm{mm})^3$ modules, stage-1-assisted partial-self-assembly.
- Stage 3 — 10^{12} $(1\ \mathrm{mm})^3$ modules, self-assembly.
- Stage 4 — 10^{15} $(100\ \mu\mathrm{m})^3$ modules, stage-3-assissted partial-self-assembly.
- Stage 5 — 10^{18} $(100\ \mu\mathrm{m})^3$ modules, self-assembly.

At the completion of any stage, it should be feasible to “clone” what has been produced for purposes of

- deploying systems for other applications,
- geographic dispersal of backup systems (and thereby also allowing {competitive and collaborative} teams to pursue alternate approaches).

5.3 Thermal Environment Considerations

The thermal environment for a MRM system is dominated by the requirements of the selected superconducting materials.

5.3.1 Magnesium diboride (MgB_2) as the primary superconducting material.

Features that make magnesium diboride attractive are:

- $T_c \sim 39$ °K.
- Low cost.
- Moderately-easy to fabricate into useful forms (bulk, wires, tapes, and thin films).

- Moderately-good chemical stability (although it's sensitive to water and moisture).
- Transparency of grain boundaries to current (strong grain coupling).
- High critical current densities.
- High critical magnetic fields.
- Large coherence length $\xi_0 \sim 4.4$ nm.
- Large London (magnetic field) penetration depth $\lambda \sim 132$ nm.
- Low normal-state resistivity.
- It is a type-2 superconductor that acts similar to a type-1 superconductor, which avoids flux-pinning issues with permanent magnet parts following temperature excursions from above-superconducting temperatures.

5.3.2 Neon-based cryogenic operating environment of ~ 20 °K.

The use of magnesium diboride ($T_c \sim 39$ °K) means that ~ 20 °K would be a reasonable application design range, which is readily attainable with cryocoolers, and is compatible with either {liquid hydrogen or liquid neon} as the cooling fluid.

The overall cryogenic requirements moderate in comparison to those needed for {large superconducting generators, or high-voltage superconducting power transmission lines}. And those requirements are extremely-modest in comparison to the hundreds of giant superconducting magnets for the CERN's Large Hadron Collider (LHC), which requires maintaining over 90 metric tons of liquid helium at an operating temperature of 1.9 °K. (http://en.wikipedia.org/wiki/Large_Hadron_Collider)

Here is some background information on cryogenic liquids:

- liquid helium boils at 4.2 °K
- liquid hydrogen boils at 20.3 °K (and freezes at 14 °K)
- liquid neon boils as 27.2 °K (and freezes at 24.6 °K)
- liquid nitrogen boils at 77.3 °K (and freezes at 63 °K)
- liquid argon boils at 87.3 °K (and freezes at 83.8 °K)

Liquid neon is generally more economical to use than liquid helium. (http://en.wikipedia.org/wiki/Neon) In terms of {refrigerating capacity per unit volume}, neon is about:

- 3 times better than liquid hydrogen
- 40 times better than liquid helium

The use of a chemically-inert material is advantageous for many advanced materials processing processes used in state-of-the-art nanoelectronics fabrication.

When {better and suitably easy to use} high temperature superconductors become available, MRM systems can bootstrap themselves into that technological realm by appropriate substitutions of {superconducting materials and cryogenic liquids}.

5.3.3 Easily creating {moderate vacuums or moderately high pressures} with thermal phase-change cycling.

For {micro-nano-SEM and CAPE-micro-nano-SEM} operation, a moderate vacuum is needed. Although moderately-high vacuums are normally desirable for conventional SEMs, the much shorter electron path of {micro-nano-SEMs and CAPE-micro-nano-SEMs} should make moderate vacuums sufficient to avoid serious scattering problems. Similar considerations apply to CAPE-based nanoelectronic systems.

A moderate vacuum can easily be formed by these steps:

- Begin with a liquid neon filled rigid enclosure sealed with {one or more} unidirectional outlet valves.
- Gently heat the enclosure a few °K above 27.2 °K (the boiling point of neon). Most of the vaporized neon will thus be expelled.
- Then let the enclosure return to normal operating temperature.
- The resulting condensation of residual neon gas will reduce the pressure several hundred fold.

An analogous process can be used to create moderately high pressures, except that (most of) the vaporized neon is not allowed to escape. This can be useful for:

- high-force actuators
- pressure-driven molding

With non-rigid enclosures, an analogous process can be used for changing net buoyancy. This can be used for

- vertical transport
- trimming the surface-relative {altitude and tilt} of floating structures

5.3.4 Using conventional silicon integrated circuitry in cryogenic environments.

Conventional semiconductor integrated circuits are not designed for cryogenic use, although there are special cases where such technology can nevertheless be used, often with substantial performance gains. (http://gtresearchnews.gatech.edu/newsrelease/half-terahertz.htm) Likewise for discrete interfacing parts, such as capacitors. This is an active topic of research for deep space missions, where operating at ambient super-cold temperatures would be advantageous. Relatively low-performance electronics may be used in MRM system modules, which lessens the challenges involved.

The simplest means for dealing with this issue is probably micro-encapsulate ICs in high-performance super-insulators, so that they can be operated at the lower end of their normal lower range of operation (typically between -20 °C to -40 °C). At device start-up, a micro-heater would bring them up to temperature, which would subsequently be maintained by their normal power dissipation.

While this approach is reasonable for $(1\ \text{cm})^3$ MRM modules, it may not be as practical at the $(1\ \text{mm})^3$ and $(100\ \mu\text{m})^3$ levels. Here, superconductivity comes to our rescue. In such cases, a special larger pooled electronics module type could be used, which would be connected to {10, 100, or 1000} near-by module groups.

5.3.5 Tolerance for occasional thermal cycling.

5.4 Superconducting Micro-Machine Technology

((**** Lots more stuff to be added in these sections! ****))

5.4.1 General considerations.

MRM-related superconducting micro-machine technology has several major advantages over conventional MEMS (micro-electro-mechanical-systems):

- near-zero stiction
- near-zero wear
- magnetic levitation (which can be applied from all directions) is extremely useful, especially since both {passive and electrically-changeable} forms are readily available
- {low-power and low-voltage} operation of {actuators and motors} are simple to implement
- assembled (non-monolithic) structures provide great design flexibility (since it is not constrained by the fairly-severe constraints of integrated circuit fabrication compatibility)

MRM-related superconducting micro-machine technology will operate at moderately low speeds. No high-speed {motors, drills, lathes, and so on} are needed. Hence viscous fluid drag from the surrounding cryogenic liquid environment is not a serious issue.

5.4.2 Superconducting micro-machine tool technology.

5.4.3 Superconducting {linear and rotary} magnetic {bearings and guides}.

5.4.4 Superconducting {linear and rotary} electric {motors and actuators}.

5.4.5 Superconducting non-contact gears.

5.4.6 Superconducting indexing systems.

5.4.7 Superconducting high-precision positioning systems.

5.4.8 Superconducting robotic systems

5.5 Other Systems Engineering Considerations

5.5.1 Supply materials

6 Future Enhancements

6.1 CAPE-micro-nano-SEMs

6.1.1 Self-improvements in major system components.

micro-nano-SEMs can be used to fabricate the special emitters needed for {CAPE-SEMs and CAPE-micro-nano-SEMs}.

6.1.2 Advanced supply materials.

Some supply material for making key nano-components are:

- Graphene
- Capped metallic carbon nanotubes
- Graphene oxide (an insulator)
- To be continued….

7 Future Prospects

7.1 Assembly Applications

7.1.1 3-d nanoelectronic module assembly.

7.1.2 Feynman atom-at-a-time nanotech

With sub-atomic-resolution position-controlled micro-machine-tool instrument-stages, an extremely-important (albeit presently fairly chemically-limited, due to reusing inherently-primitive-but-readily-practically-available hybrid-AFM-with-STM-sub-mode atomic-placement mechanisms) subcategory of Feynman's atom-at-a-time material-synthesis scenario can be practically-realized.

7.2 Exploiting Cryogenic Liquid-Gas Interfaces

The {large and sharp} density-gradient of liquid-gas interface for cryogenic MRM-micro-nano-SEM systems may be exploited as a {buoyancy-determined positioning system, and as an extended precision reference surface}.

7.2.1 {Large-scale, ultra-light, and high-precision} {flat and focusing} reflecting optics.

{Flat or parabolic (when rotated)} cryogenic liquid surfaces may be used by floating MRM-micro-nano-SEM modules for purposes of hybrid micro-nano fabrication of large-scale (10+ m diameter) mirror-support structures. Once formed, other more-conventional processes would be used to deposit additional mechanically-strengthening material onto the underside of the skeletal micro-nano lattice. A subsequent standard (for example) vacuum-aluminization step would provide the final topside reflecting surface.

These would initially be very useful for upper-stratospheric {astronomy and surveillance}.

As production prices declined over successive decades, such mirrors would also become useful for above-the-weather mid-stratospheric tethered-armadas of sun-tracking solar-electric power-station concentrators.

7.2.2 Floating hybrid {Venice-like and jelly-fish-like} MRM system architectures.

8 General Future Implications

Practically-demonstrated construction-universality of superconducting micro-magnetic sub-atomic-precision micro-machine-tool-subsystems with only micro-precision-level fabrication-technology will be a tremendous technological coup. All the successive-generations of increasing nano-process-content (up to attaining production-prototype-capability-threshold for bootstrapping primitive self-multiplying nano-automata-production-systems) will of course also be super-wonderful secondary-coattail-rider-derivatives.

9 Conclusion

To be continued…

10 References

((Add ref to my book chapter from the First Artificial Life conference proceedings.))

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