

Cognitive Microsystems: Geometry of Computation and Sensing

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Abstract

We describe one possible approach for the development of generation-after-next microsystems that will have on-the-fly sensing and processing adaptivity. These microsystems should be viewed as the lowest level in a multi-tiered network. Ideas for the design, manufacture and integration of these microsystems borrow heavily from several evolving fields, including origami folding, computational geometry, topology, photonic band gap structures and three-dimensional nanofabrication techniques. This work is driven by the “geometry of computation and sensing.” In other words, how do the spatial structures of computational and sensing devices define their properties, and, more importantly, can we use geometry as a design tool? Ultimately we envision families of microbots, built from cell-like modules analogous to stem cells, which can not only learn and adjust to their environment but furthermore can adapt their form and function to accommodate possibly *changing* environments.

1 Introduction

There has recently been a great deal of interest within the defense community in the idea of biologically inspired multifunctional dynamic robotics. Of particular interest is the use of bionic military devices that act as information interfaces to the overall military system-of-systems architecture. Much of this interest stems from recent conflicts in Afghanistan and Iraq, where Special Operations

Forces have assumed a significantly greater combat role. The Department of Defense has a number of ongoing efforts to enhance and extend the current capabilities of the individual soldier and is exploring ways of integrating this function within the system-of-systems architecture.

Intelligent microsystems present numerous opportunities for future defense systems. One obvious motivation for miniaturization is the small form factor, which enables these small but powerful systems to unobtrusively infiltrate spaces that are otherwise difficult to access. Moreover, the use of miniature features approaching the nanoscale (<100nm) in microsystems often provides access to new physical properties and, hence, unprecedented functional capabilities. The challenge then is to integrate nanofeatures with more traditional micro- and macro-elements in ways that allow them to function in challenging environments, such as urban battlefields and counter-terrorism operations.

The following features will maximize the utility that defense systems can derive from intelligent microsystems:

- Integration of hybrid functions: chemical or biological reactors, optical sensing, digital electronic logic, mechanical motion for movement or energy harvesting, *etc.*, in the same package and in a way that facilitates interactions between the different modalities;
- An expressive interface across dimensional scales from the nano to the macro (where humans live

and operate) with maximum efficiency, interoperability and control;

- Reconfigurability, so that the system can adapt its function to the changing requirements of complex missions. This is particularly important for missions where the operational environment is not, or cannot, be known *a priori*; and
- Large scale manufacturability, so that yield, reliability and cost are commensurate with a wide range of deployment strategies. Cost and yield may also be improved if modular building blocks can be combined with reconfiguration strategies to enable a family of morphing robots.

The first three features point to the requirement of three dimensional (3D) integration; any planar architecture would quickly run into physical limitations. However, 3D nanofabrication has not yet reached the level of industrial maturity that is commonly achieved with 2D technologies. We believe that an efficient way to reconcile manufacturability of nanosystems with the 3D requirement is to utilize 2D technologies to the maximum degree possible. This is the primary motivation for our research.

In this paper, we explore the intriguing idea of reconfigurable robots that are constructed out of a number of modules [1]. Structural modularity is a key enabling concept for multi-functional robotics, and, in fact, we extend the idea of reconfigurability to also include sensors and processors. The two figures below, extracted from reference 1, illustrate two broad classes of morphing robot structures. Figure 1 shows a lattice robot design, while Figure 2 shows a chain robot design.

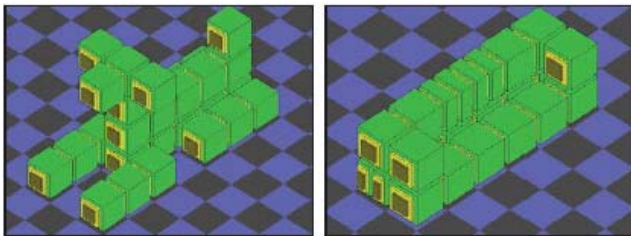


Figure 1: Lattice Robot Design



Figure 2: Chain Robot Design

In Section 2, we describe our system-level vision with a particular focus on two primary technology thrusts. The

first technology focus is on the design and fabrication of 3D sensors and processors using “Nanostructured Origami™.” The second technology thrust is the folding and unfolding of polygonal linkages as emerging in structural biology applications.

2 System-Level Vision

We envision a family of cognitive microsystems that function as the lowest level in a multi-tiered network architecture. These microsystems would be carried by, and provide support for, miniature-Unmanned Aerial Vehicles (MAVs) and miniature ground robots.

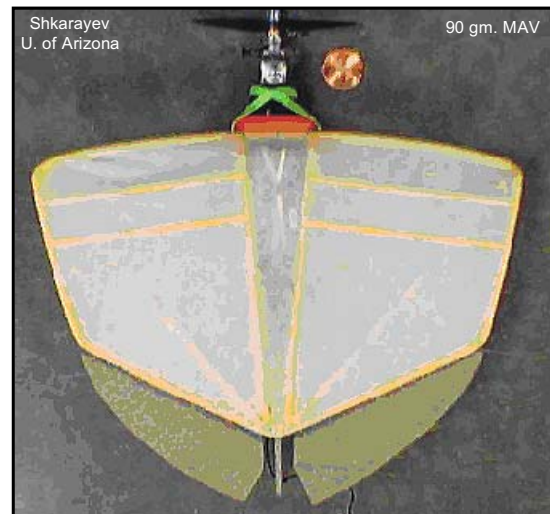
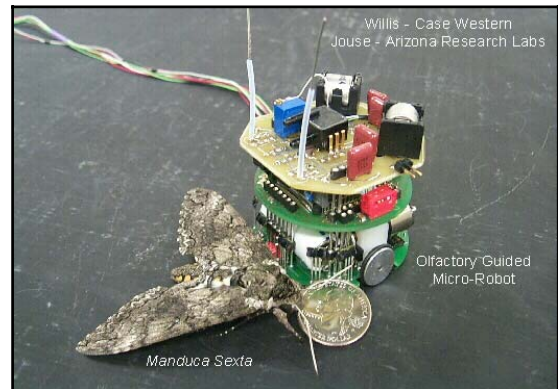


Figure 3: Ground and Air Robot Designs

For example, a small robot could be used to inject the cognitive microsystems into personnel for surveillance and tracking purposes or into friendly forces to provide very reliable Identification Friend or Foe (IFF) capabilities. These small robots could also inject the cognitive nanosystems into personnel to effect changes at the DNA level. The MAVs might carry cognitive microsystems that possess some sensing and processing capability to further extend the soldier’s senses beyond even that provided by the MAVs themselves (a concept also known as “enhanced reality”). Analogous to the applications currently envisioned for distributed sensor nodes, the cognitive

microsystems could be dispersed by MAVs to form self-organizing, self-healing, *adaptive* sensor networks. The cognitive microsystems could be equipped with antimatter warheads and would then have a very intriguing potential application for decontaminating chemical, biological and/or nuclear hazards.

An interesting challenge associated with adaptive cognitive bionic devices is the learning or reinforcement of desirable configurations. Results from machine learning, including the “ugly duckling theorem [2],” indicate that without external bias (*i.e.*, a concept of a goal or desirable state), learning (intelligent adaptivity) cannot occur, as all states or configurations are equally “valid.” The incorporation of learning in bionic systems remains an active area of machine learning research. We now provide a more in-depth discussion of our technology focus areas: Nanostructured Origami™ and the modeling of polygonal linkages.

2.1 Design and Fabrication of 3D Nanostructures

The Nanostructured Origami™ 3D fabrication and assembly process is a novel approach to the manufacture of 3D nanostructures by folding two-dimensional (2D) nanopatterned membranes that has been developed and demonstrated at MIT [3]. The manufacturing process consists of two steps. During the first step, 2D nanopatterning of a flat membrane takes place, including the definition of the folding apparatus (*e.g.*, creases and actuators). Subsequently, a “folding sequence” is initiated, resulting in the nanostructures taking their desired configuration in 3D space in the final folded structure. A simple case study, including the design, modeling, fabrication and testing of a single folding silicon segment with gold hinges, has been carried out with funding from the National Science Foundation. We have achieved folding rotations up to 180° with sub-msec actuation times and alignment better than 10 μm.

Three key functional requirements of nanosystems motivated our approach:

- Bridge the nano- to the macro-scale;
- Integrate components of hybrid functions, such as electronic logic, optical sensing, mechanical reconfiguration, *etc.* in the same system; and
- Utilize state-of-the-art 2D nanopatterning technology for 3D nanofabrication to the maximum extent possible.

Additionally, we require the 3D nanosystems have the following functional requirements:

- 3D connectivity;
- Heat dissipation;
- Scalability, in terms of both volume and surface;
- Platform compatibility with nanofabrication and macro-packaging technologies; and

- Low cost, high yield and repeatability.

An interesting analogy between such an intelligent microsystem and the familiar macro-world is a car engine. The engine contains numerous hybrid functions, *e.g.*, pumps, electrical chargers, combustion chambers, transducers to mechanical energy, cooling systems, sensors and controls. These are assembled in the factory by robots, which follow a very precise schedule to ensure that the components are inserted in the correct order and position. The difference between this kind of assembly and assembly of systems at the micro-nano scales is that the latter is lacking manipulation tools that can function with sufficient accuracy and throughput. For example, Atomic Force Microscopy (AFM) is accurate but serial by nature (even arrays of AFM tips cannot achieve the degree of parallelism of, say, a lithographic tool). On the other hand, self-assembly is highly parallel but it provides very limited degrees of control and typically results in quasi-periodic structures only. Nano-structured origami can be thought of as a “templated self-assembly” method. It achieves high throughput because features are defined via 2D lithography, while the location of the creases and the folding sequence (the order in which the creases are folded) exercises control over the assembly process. Thus, highly complex, non-periodic 3D structures can be manufactured with accuracy, reliability and throughput comparable to those of conventional 2D lithography. The design of Nanostructured Origami™ proceeds according to the flow chart below.

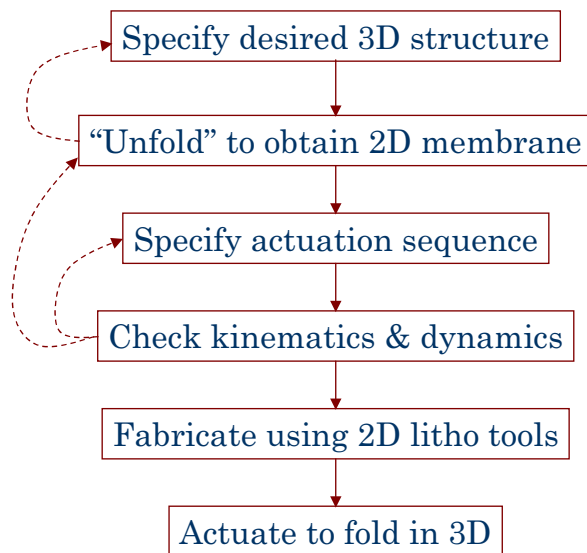


Figure 4: Flowchart for Nanostructure Origami

The primary appeal of the Nanostructured Origami™ 3D fabrication and assembly process is that the fabrication of discrete elements is decoupled from the assembly process. Thus, almost arbitrary non-periodic nanosystems can be assembled with minimal time and cost because nanopatterning takes place in a single step for the entire 3D system, and the folding step is fast and inexpensive.

In designing more physically realistic, *i.e.*, complicated, application-oriented nanostructures such as nanosensors, one should almost certainly use a “backwards” type of design technique. This is because, in general, it is much easier to work backwards from a complicated, conceptual design, “tearing it apart” from its final 3D configuration until one ultimately reaches an “initial” configuration pattern on a flat, 2D membrane.

In our demonstration of Nanostructured OrigamiTM, Si is the segment material, and flexible Au wires act as hinges. A prototype for a simple, single-segment origami structure is shown in Figure 5. The Au hinges served a second purpose as actuators using the Lorentz force method. Current passing through the portion of the wire near the end of the segment, oriented perpendicular to an externally applied magnetic field, produces a force that rotates the flap out of plane.

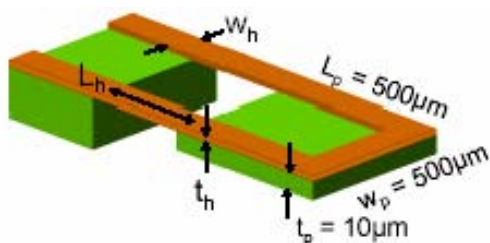


Figure 5: Solid Model Representation of Prototype

The Lorentz force actuation method is scaleable up to a few segments. For structures requiring ~ 100 or more folds, an alternative folding strategy uses engineered residual stress to curl layered thin films. Using a 50 nm film of Si_3N_4 and 25 nm of Cr, we experimentally created 180° curls with radii of curvatures on the order of 250-400 nm. Work has begun on fabricating stacked diffractive optical elements using the Nanostructured OrigamiTM approach. These could serve as building blocks for arrays of tunable optical tweezers. Other actuation mechanisms have been proposed in the literature, *e.g.*, interface strain, electro-strictive polymer and surface tension. Each of these methods may have advantages for a given application or system design.

In addition to bridging the gap from nano-scale to micro-scale and decoupling the 3D hybrid assembly process from the 2D nanopatterning step, additional advantages accrue to this manufacturing process. Massive yet manageable connectivity is possible throughout the volume, in conjunction with organized architecture, inexpensive development and production costs, superior thermal management, and the ability to scale indefinitely. Also, the decoupled nature of the fabrication and assembly makes the Nanostructured OrigamiTM 3D fabrication and assembly process suitable for a broad suite of application areas, including microelectronic, microfluidic, optical, biological and hybrid systems – just what is needed for manufacturing nanosensors and other general-purpose nanosystems with high reliability and yield, and with low cost.

2.2 Computational Origami.

The Origami Folding problem can be easily stated. Imagine making creases in a flat sheet of paper, and then folding the paper along the creases without tearing, stretching or bending the paper, to obtain a 3D origami shape. The planar regions bounded by creases are assumed to be rigid, more like metal sheets than paper, and the pieces are not allowed to go through each other during the motion. *Are there origami shapes which are compatible with the creases and the induced metric of the paper, but which cannot be folded by such a process? And if all can be folded, how can one design a folding pathway, described perhaps as a sequence of simple motions that could be executed mechanically?*

Computational Origami is a relatively recent endeavor in Mathematics and Computer Science, see [8] for a survey. The published literature addresses questions of feasibility, characterization and NP-hardness of flat-folds, as well as applications [9-11]. According to Tom Hull [12], only two published articles deal with the mathematics of rigid origami [13-14]. However, a very recent result [24] solves completely the problem for one-vertex origami folds with non-self-intersections.

The topology of the configuration space for spherical linkages and single-vertex origami folds (allowing self-crossings) was previously studied in [15-16]. The problem is related to the well studied topic of polygonal linkages in the plane and in space, which has received a lot of attention in recent years. Relevant for our paper are the results on the Carpenter’s Rule Problem using expansive motions [17] and pseudotriangulations [18] and the examples of locked spatial linkages [19-20].

Single-vertex origamis are directly related to planar polygonal linkages, which are simple polygonal paths (open or closed), embedded in the plane with fixed edge lengths. In general we assume that the edges of the polygon (links) can rotate freely around the vertices (joints). An expansive motion never decreases any interdistance between two points and thus guarantees non-self-intersections. In dimension two, the infinitesimal expansive motions are well understood. They form a polyhedral cone [23] whose extreme rays have a combinatorial characterization, given by pointed pseudotriangulation mechanisms [16]. They have been instrumental in providing two solutions to the Carpenter’s Rule problem for simple planar polygonal linkages, [17-18]. Their 3D counterparts also form a polyhedral cone, defined by similar linear inequalities, but finding a combinatorial interpretation for its rays has remained elusive and has become recently a theoretical problem of considerable interest.

2.2.1 Spatial Polygonal Linkages

This section discusses current research being performed by Streinu under the NSF/DARPA CARGO program. Specifically, this work addresses the folding and unfolding processes for polygonal linkages in two and three

dimensions. The primary focus here is on fundamental mathematical properties and novel algorithmic approaches, with application to protein folding. We believe that this line of research is directly applicable to the nanomanufacturing method described in the previous section. As demonstrated by the connection established in [24] (and briefly discussed in 2.2.2) between certain spatial linkages and single-vertex origami, this line of research is directly connected to the current project. One clear connection is in solving the inverse kinematics problem for single-vertex origamis. Research on this and more general cases is currently in progress by our team and will be described in more detail in Section 2.2.2.

Structural biologists are relying on a variety of theoretical models and computational techniques to address the protein folding problem. Molecular Dynamics and Monte Carlo simulations are the most widely used methods, but even the fastest computational power available today has been defeated by the size and complexity of the problem. A novel, qualitatively different insight into how to perform such computations is needed, but the mathematical and algorithmic foundations for such work have not yet been sufficiently investigated and developed. The CARGO project aims at going straight to *the geometric roots of the problem in search of novel and unexplored properties of protein-like shapes, to develop a sound mathematical theory for folding processes, and to turn it into efficient algorithms that structural biologists can effectively use.*

The approach relies on the assumption that the *geometry* of protein molecule backbones can be accurately modeled as 3D polygonal linkages with fixed edge (bond) lengths and vertex angles (the bond angles). For realistic simulations, this model must be used with *self-avoidance interactions*, and supplemented with an appropriate *energy model* accounting for repulsive and attractive forces between the atoms.

The key goals of this research are:

- To understand the fundamental topological properties of certain families of 3D mechanical linkages, including polygonal chains with prescribed edge lengths and vertex angles (protein backbones);
- To obtain efficient data structures and algorithms for detecting important folding events (such as self-contacts), based on 3D generalizations of *pseudo-triangulations* or other methods;
- To use the above tools to obtain efficient representations and algorithms for modeling self-avoiding motions of polygonal chains in the presence of an energy field;
- To apply these to several motion planning and motion analysis problems arising from the study of protein folding processes; and
- To produce prototype implementations of these ideas.

The starting point is to work on generalizations of the recent successful rigidity-theoretic approaches based on pseudo-triangulation mechanisms. The rigidity-theoretic techniques have allowed the definition of 2D motions that are purely expansive or contractive (the former can guarantee that a chain will not self-collide). Extending these techniques to three dimensions has the goal of developing efficient data structures and algorithms for planning, analyzing, approximating, tracking, and querying such motions. The study of linkages is rather unique in that a broad variety of tools has been brought to bear on its analysis over the years.

The proposed unfolding algorithm in 2D was based on a novel class of one-degree-of-freedom mechanisms induced by pseudo-triangulations of planar point sets. The main idea of the approach of [18] is illustrated by a motion-planning problem: how to continuously reconfigure a simple planar polygon to any other planar configuration with the same edge-lengths while remaining in the plane and without creating self-intersections along the way. The algorithm efficiently solves the “Carpenter’s Rule Problem,” which is stated as follows: convexify a simple bar-and-joint planar polygonal linkage using only non self-intersecting planar motions. A step in the convexification motion consists in moving a pseudo-triangulation based mechanism along its unique trajectory in configuration space until two adjacent edges align. At that point, a local alteration restores the pseudo-triangulation. The motion continues for $O(n^3)$ steps until all the points are in convex position.

2.2.2. Recent Results on 3D Origami Folds

In [24], the authors introduce a class of provably expansive motions in 3D and are exploring untangling techniques based on them. They apply them to unfold spherical polygonal linkages of total length no more than 2π and spherical paths of total length no more than π . The proofs are based on natural extensions to the sphere of planar Euclidean rigidity results regarding the existence and combinatorial characterization of expansive motions. As a consequence, they have formulated a first necessary condition that 3D generalizations of pointed pseudo-triangulations must satisfy. They also reduce several other problems to the spherical case, such as single-vertex origami folds and panel-and-hinge structures with incident axes.

This work proves that, for a single vertex origami structure, all simple folds are reachable from the open flat state. Their main result is formulated in terms of spherical polygonal linkages of total length no more than 2π . They show that every such simple spherical polygon can be unfolded to a convex position using a finite sequence of $O(n^3)$ simple motions induced by one-degree-of-freedom spherical mechanisms based on spherical pseudo-triangulations. The proof relies on a natural extension to the sphere of the planar Euclidean results regarding the existence and combinatorial characterization of expansive motions.

Based on these theoretical results, we have started recently developing an implementation of the unfolding algorithm described in [24], based on the planar polygonal case of [18]. In the future, we expect to develop this into a powerful software simulation tool for designing folding pathways for more complex origami shapes, while simultaneously developing the mathematical and algorithmic theories that provide the theoretical underpinnings for our ability to fully automate such simulations.

By assigning one bar to each segment of a folded origami structure, we can convert the origami unfolding problem to the motion planning problem. The bars are connected so that they form a closed mechanism. We refer to this mechanism as a “skeleton” (in Computer Graphics, this is sometimes referred to as a “bone structure.”) To solve the unfolding problem, we start with a folded origami structure, and project the skeleton on a plane coinciding with the plane where the structure will eventually be unfolded. We then apply the unfolding algorithm, obtaining a sequence of motions which converts the projected skeleton to a convex polygon.

The next step is to refold, *i.e.* apply the previous sequence in reverse. For certain simple motions, this can be done efficiently and elegantly using Screw calculus [6, 7] to track the motion of the segments. We are developing a software suite for unfolding/refolding and origami motion visualization.

3 Conclusions

We have described one possible approach for the development of generation-after-next microsystems that will have real-time sensing and processing adaptivity. An interesting take on networking that may have relevance here is given in [25]. Our proposal ties together the design and fabrication of three-dimensional nanostructures with mathematical approaches to folding and unfolding of polygonal linkages in three dimensions in a very productive manner. We believe that our exploration of geometry/topology as it pertains to information routing that occurs within processing systems such as nanosensors and microsystems will lead us to novel insights and applications for future Defense-related and civilian systems. For example, a more speculative idea is to use the Nanostructured Origami™ 3D fabrication and assembly process to manufacture nanoscale elements within the confines of a photonic band gap structure [26-28]. This might allow the manipulation and control of the system’s energetics and thereby constrain the possible folding/unfolding paths.

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