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The Hyperpatch Chronicles:
An American Engineer's Tale

Edward L. Stanton
CTO Emeritus
MSC Software Corporation

**"design is what sets engineering apart
from the sciences"**
Dr. William Wulf
President of the National Academy of Engineering

The Hyperpatch Chronicles

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The Hyperpatch Chronicles

Theme:

The chronicles are a blend of hyperpatch solid modeling technology and the market events that enabled a small company research project to become a global software business. It is also a personal history of finite element modeling and the role of Hermite polynomials in early computer aided geometric design.

1. Introduction

At first this small monograph was about solid geometry models written by a practicing engineer who designed 1960's NASA finite element software tools. Those tools were for modeling materials and structures used in the Apollo program. That technology is very interesting to me but the story of early software industry events was even more interesting to many early readers and the focus was expanded. The chronicles grew to include global commercialization events from several industries but mostly aerospace, automotive and materials.

A common thread that runs through the chronicles is the recurring role of Hermite polynomials in analysis and design. It is ironic that these polynomials used so successfully to model surfaces and finite element geometry are associated with a mathematician who did not particularly like geometry. Hermite was interested in analysis not design. A second thread is how 1960's finite element modeling research moved from rocket science applications to a commercial software business.

Many of the models in the monograph were created using technology first developed for NASA in the 1970’s. The original software generated 3D finite element models for a NASA structural analysis program called Nastran. That 1978 NASA modeling system, Patran, has evolved to include many other geometry models but Hermite polynomials continue to be used for difficult material geometries including 3D nanostructures. Collaboration among individuals and organizations is a big part of the global software business story.

1.1 Early Life Experiences

As a summer intern in the 1950’s working for the US Bureau of Reclamation on a survey party in the Arizona desert, the industrial importance of geometry quickly became apparent. Daily use of trigonometry to check the construction accuracy of the Welton Mohawk canal then being built took geometry from the classroom into the field literally. That summer also added real world uncertainty to the Euclidian notions of exact mathematical models taught in the classroom. The planet we live on is a constantly changing object covered with surface plates that slide past and over each other. The benchmarks we checked in the field had to be adjusted for relative motion that had occurred since the benchmarks were first placed only a few years earlier. As a rod-man I learned the measurements we were taking also had small errors because the rod being read was never held exactly vertical among other things.

About that time I was learning solid geometry from a remarkable teacher, Ms. Leah Forsman, who had her students construct the five Platonic solids and enter them in a small science fair. The class won a prize for an icosahedron made into a star-polyhedron from poster-board templates. That lab exercise was an introduction to flat patterns that fold up to form a solid object in the real world. Finite thickness poster-board patterns do not fit together exactly the way that zero thickness mathematical surfaces do when forming a virtual Platonic solid. We will revisit uncertainty later when robust design methods are described as a way to anticipate and prevent many design errors in practice.

Early real word experiences, like these, provide an application context for classroom models that help bridge the gap between theory and practice throughout life. Nature reveals new secrets to each generation at an ever-increasing pace and that makes it more important, not less important, for each generation to have both actual lab as well as virtual lab classroom experiences. Why, because the practice of engineering is about product design and must deal with the uncertainty found in geometry as well as in materials, loads and markets. Uncertainty can range from normal Gaussian, to extreme-value driven and wildly asymmetric.

Also of concern today is why so few students' study engineering at many Universities when industry often complains it cannot find enough innovative young engineers. Supply and demand don't seem to be working at first glance and this monograph will argue that the failure to keep design programs in engineering education at research universities is one of the reasons. Design is what sets engineering apart from the sciences to quote Dr. William Wulf a recent President of the National Academy of Engineering. Years ago as a young Aeronautical engineer it was clearly the case in the wind tunnel where I first worked.

1.2 Early Digital Geometry Models

At Douglas Aircraft in Santa Monica many years ago two remarkable engineers, Harry Meriwether and Art Eshelman, introduced me to parametric cubic geometry models. Art was an early adopter of computers in aircraft structural design and he also managed that department. Art favored Hermite polynomials because their bicubic surface patches (Coons surface patches) fit together smoothly and without gaps. Gaps in articulated surface models remain a problem to this day for optical applications that must be light tight. Boolean operations now common in computational geometry can produce objects that have very thin slivers and gaps when best practices are not used.

Coon's surface patches also have the property that only nodal values on common edges are needed to assemble patches to form a smooth structure. This is very useful in the design of ship structures. Steven Coons was at MIT in the 1960s and the Navy applied his research to the computer-aided-design (CAD) of ship hulls. That technology was a natural for aircraft structures as well because they too require smooth surfaces for similar fluid flow reasons.

My first job at Douglas Aircraft was analyzing wind tunnel models and later conducting flight test experiments for missiles and space launch vehicles. Harry Meriwether and I were teamed on a flight test project in 1962 using a very innovative Monte Carlo flight loads measurement method that he had developed. That project was my introduction to Monte Carlo methods and to what most now call computer

aided modeling and simulation. I used an early digital computer to simulate the flight loads and Harry used strain gages and Monte Carlo methods to measure them during flight tests. They matched so well that post flight statistical analyses could not find a meaningful difference in the two data sets. I was too young to realize it would be years before that happened again.

Harry's take on parametric cubics was that nothing more than a cubic was required for design because they could model inflection points. We and a few other engineers at Douglas interested in digital geometry models acted as an informal "Parametric Cubic or PC Club". Mike Mortenson and Hank Timmer were two of those engineers and Mike later wrote a series of books on computer graphics that I like for their illustrations and cogent writing style. He is especially good at illustrating how the conic sections and other classical shapes can be modeled locally with parametric cubics.

1.3 Early NASA Finite Element Models

In 1964 Douglas Aircraft had a visit from a NASA engineer who was trying to persuade industry to support the development of a NASA structural analysis system for the Apollo program. Every stage of the Saturn launch vehicle was being designed using different matrix methods for structural analysis, which most contractors refused to share. As systems integrator, NASA wanted digital design data delivered using a common model for launch vehicle analyses. That extraordinary NASA engineer was Tom Butler and his vision became Nastran but only after an epic personal struggle. Nastran introduced computer-aided

design and analysis methods to engineers around the world. Tom lived just long enough to see the beginning of those changes.

The first NASA Nastran Users Conference was held in 1971 at NASA Langley. In less than ten years Nastran had become a phenomenon among structural designers including engineers from Ford Motor and other auto companies. This was a period of rapid expansion in the use of finite element analysis (FEA) in vehicle design. That growth was being gated by the very long time it took to create a vehicle finite element model. A fairly basic wing structure could take several engineers up to three months to model with simple bars and shear panels working on drafting boards. Something needed to be done to speed things up and improve quality. Creating digital geometry data from paper drawings was not only a very slow process it was error prone. This was long before robust CAD systems became available.

The NASA Nastran Systems Management Office issued a specification for a finite element “data generator” in 1977 and asked Prototype Development Associates (PDA) for a proposal. PDA was a small company I had joined in 1975. The NASA specification contained a requirement for solid geometry finite element models for composite material applications. That NASA request was the beginning of digital geometry based finite element modeling (FEM) as we know it today. The introduction of the VAX minicomputer by Digital Equipment Corp. (DEC) in early 1978 with virtual memory and individual user terminals made the project possible on a very limited budget. NASA not only led the drive to put a man on the moon, NASA research projects led to other innovations including early

software for computer-aided-engineering (CAE) on large vehicle design projects.

The “data generator” contract was awarded to PDA in 1977. PDA had proposed using Hermite parametric cubic geometry models for the finite element data generator. The plan was to interactively generate Nastran finite element data from *reusable* Hermite geometry data. One key to success was a software architecture that separated geometry modeling and finite element modeling into two “phases”. That was my idea and while a pretty simple one it worked well.

We used construction-in-context scripts for geometry modeling and introduced a name-object-operation-data-list “NOODL” rule long before object oriented programming tools became available. We used this primitive scripting language to allow the modeler software to run in batch and interactive modes. The “NOODL” rule was motivated by Joseph Weizenbaum’s book “Computing Power and Human Reason” especially the story behind ELIZA. Making it possible to interact in a conversational way with computer software was and still is powerful stuff.

Lou Crain, Neil Harrington and I developed the NASA prototype software that we called Patran and PDA later added graphics when the DEC customers buying VAX computers also bought graphics terminals for their engineers. Lou was a dynamic young MIT computer scientist and Neil was a gifted senior engineer expert in application software development. That collaboration turned a small NASA project into a very successful new business within PDA, which soon turned PDA into a global company. PDA later went public in 1985 when

the company began earning more from FEM software than from prototype aerospace hardware.

When a new technology succeeds commercially, especially one leading to an Initial Public Offering (IPO), people often ask how did you know? The usual assumption is that someone must have anticipated the market opportunity and created a killer new business development plan. We really didn't plan in the MBA sense to become a software company. PDA just filled orders from DEC customers until even I realized the FEM market was big and getting bigger very fast. At that time I was busy designing and testing carbon-carbon structures for rocket motors using Patran. In the mean time DEC salesmen were asking PDA for help with sales calls at customer sites all over the country.

Yes, we had created arguably the first solid modeler for FEM but much of that early commercial success was driven by the new VAX minicomputer and by new low cost color graphics devices; both these market events were external to PDA. Also, Dick MacNeal and Bob Schwendler had developed a commercial version of Nastran that took FEA beyond the aerospace industry and into global automotive markets. The explosive market for FEM was created largely by these external events. When new VAX customers needed a 3D finite element modeler for Nastran, including computer graphics, PDA quickly invested in developing Patran-G. That product decision was made by PDA's management team then led by John McDonald a former head of Sandia's materials lab. Rapid prototyping was a PDA core competency and we quickly adapted it to designing software products. Lou Crain was the one who first responded to the opportunity and with DEC help put

together a sales and marketing plan for Patran-G. At the second Patran Users Conference in 1984 Lou gave a paper that detailed the early releases of Patran-G and acknowledged the many PDA engineers involved.

Like other small business Government contractors PDA was motivated to commercialize advanced technology research as part of a Government policy encouraging dual use R&D cost sharing. Patran-G was not the only commercialization story at PDA but it was the one that benefited the most from external market events. Others were actually hurt by external market events. We manufactured a Thermoshield for the oil drilling industry based on PDA vacuum welding technology. It sold well for a while but volatility in oil industry markets kept our Petroleum Products business from being as profitable as we had hoped. The point of this aside is to emphasize the importance of being flexible and having a culture like PDA's that encouraged everyone to look for commercialization opportunities. It also helped to be a small company populated by extraordinary people.

2. Hermite Polynomial Geometry Models - FEM

Let's begin the chronicles with basic Hermite cubics and work our way up to hyperpatches. The coefficients for cubic Hermite polynomials are linearly related to those for Bezier cubics, algebraic cubics and all cubic polynomials. What makes Hermite polynomials so special in design is the localization of nodal parameters needed to control spatial assembly. Hermite cubic curves, bicubic surface patches, and tricubic solid hyperpatches can be connected exactly to adjacent finite shape geometries with slope continuity on their entire common boundaries. This is true for one, two and

three-dimensional Hermite geometry models. In the time domain Hermite polynomials are also special because they are the solution to Schrödinger's equation for the harmonic oscillator problem in quantum mechanics. Here the localization is in the frequency domain where they correctly predict that the probability of electrons sharing an orbit is zero unless they have adjacent quantum numbers.

Assemblies of Hermite cubic lines, patches and hyperpatches are constructed using just the four cubic Hermite polynomials. Nodal values can be "blended" to model conforming shapes (smooth surfaces) with slope continuity. This is very important in continuum mechanics for modeling the deformations of beams, shells, and solids. It is also important in structural mechanics, which uses beam elements and lumped mass elements to model the elastic behavior of semi-moncoque structures. Interestingly the vibration modes of carbon molecules, including C60 fullerenes, can be modeled using these same finite elements. Recently Patran was used to model the vibration modes of several single walled carbon nanotubes (SWNTs) using nanotube atomic coordinate data from the Web. NASA Patran had a neutral file input format that could be used to exchange molecular coordinate data in chemical markup language (CML) format with a wee bit of editing. I note in passing that CML data files were used to test the W3C XML standard before it's first release. Open international standards like CML and XML are crucial for design collaboration and for the Web itself in my opinion.

Getting back to the monograph theme, the first application of hyperpatch geometry models was to create 3D composite finite elements for the Navy. The design of attachments in aircraft composite wing structures was the Navy application and it was that project which led to the extension of Coon's work to tricubics. The Navy needed to model 3D interlaminar stresses causing early aircraft composite structures to delaminate near attachments. This project started before I moved to PDA and was completed there. I had won the AAIA / Office of Naval Research prize that year which made the move possible. We called the tricubic Hermite solid model a hyperpatch. Most of my colleagues considered the name hyperpatch arcane but today with hypertext and hyper-threading such common terms, hyperpatch almost sounds ordinary.

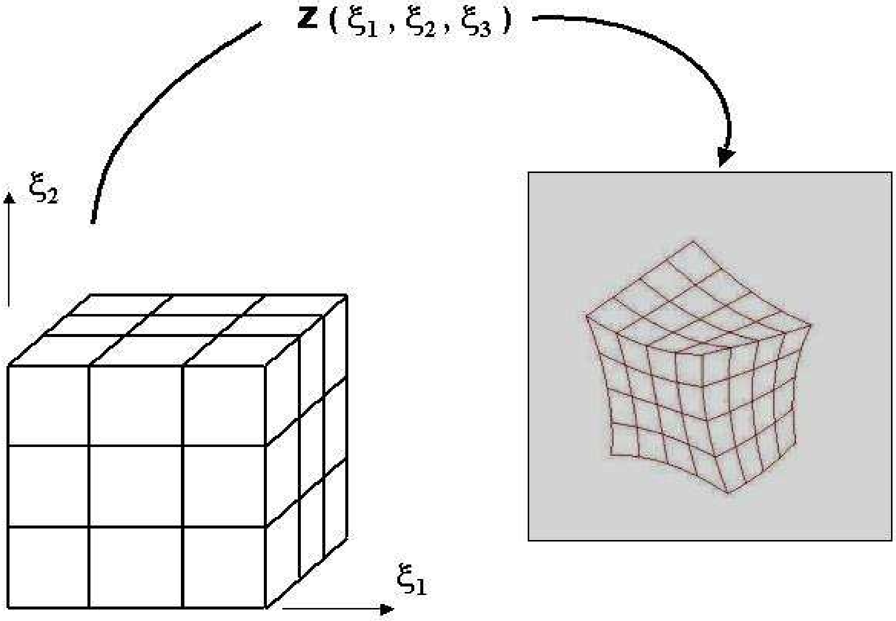
The Navy first became interested in Hermite finite elements a few years earlier when a bicubic Hermite shell element of mine with 16 nodes predicted stress concentrations that compared well with photoelastic test results. That work was done at McDonnell Douglas and is described in a paper I wrote with Ed Palacol in 1973. A graphic in that paper comparing strain contours between test and analysis was compelling. Harry Meriwether and Richard Snell produced the comparison graphic shown in the paper. At that time, most project engineers still did not accept FEA simulations for design verification. However, comparisons like this were the beginning of a rapid decline in photoelastic lab testing at many companies in order to cut costs.

2.1 Basic Definitions

In mathematical terms tricubic hyperpatches are the same whether being used for FEA or FEM and one of the

first tasks on the Navy project was to work out efficient transformation equations between tricubic Hermite polynomial formats. The term format here refers to the four algebraic, geometric or point coefficients used to define the cubic Hermite polynomials for calculation. Certain operations like model assembly are best done in geometric format while algebraic is more efficient for the integrations required to generate stiffness matrices. A set of utilities for rapidly transforming hyperpatches from one format to another became part of a math library that we used on several software projects.

Parametric cubic models in this monograph are length normalized to the unit interval for each coordinate function $z_1(\xi_1)$, $z_2(\xi_2)$, and $z_3(\xi_3)$. A unit interval [0, 1] for ξ improves model conditioning for digital geometry computations. Note that others sometimes use the interval [-1, 1] for normalizing coordinate functions and both intervals work well for finite geometry computations. In the monograph we will suppress the coordinate subscript if it is not needed for clarity. I find it interesting to note in passing that Pixar's RenderMan software includes bicubic Hermite surface patches as one of their geometric primitives. They also use unit interval [0,1] normalization but retain Coon's (u,v) patch notation. Ed Catmull in his Ph.D. Thesis developed an algorithm for the computer display for bicubic curved surfaces. He was often at SIGGRAPH Conferences when NASA Patran was being developed. His software became a movie industry standard interface and every visual effects Academy Award winner in recent years has used RenderMan. Today imaging software is part of the natural sciences including biomedical applications.



$$\mathbf{Z}(\xi_1, \xi_2, \xi_3) = z_1(\xi_1)\,e_1 + z_2(\xi_2)\,e_2 + z_3(\xi_3)\,e_3$$

In this image the unit cube has uniform one-third points that are mapped into a hyperpatch and then meshed uniformly into sixty-four solid elements. Non-uniform finite element meshes can be generated as well. Also, note the hyperpatch mapping can be degenerate so that tetrahedrons, wedges and pyramids can be generated from the unit cube. In the terminology used by animation studios, the hyperpatch can "morph" into any of these shapes. It is also important to remember that the solid geometry model and the finite element model in Patran are created in separate phases. This allows tessellation and other algorithms to be used to mesh a hyperpatch independent of the mapping (morphing) used to create the spatial geometry model. Today there are many such algorithms in MSC.Patran but there was only hyperpatch parametric meshing in NASA Patran.

Interestingly it is also possible to pave three sided shapes with four sided patches. This is illustrated by paving an isosceles triangle with three identical quadrilaterals. This paving is actually found in nature on the surface of icosahedral virus structures and often illustrated in books on protein structures. Nature uses icosahedral symmetry for genetic economy. Only one gene is needed to code for the entire protein shell.

Needless to say none of us on the NASA Patran development team 30 years ago knew anything about protein structures. The longevity of the finite element method is remarkable. New applications like molecular structures and nanostructures that appear first in research journals and then in MEMS and NEMS applications keep happening. Finite element models are even used in computational finance today. I used to look for signs that the market for finite element applications had stopped growing. That will surely happen at some point but I have stopped looking.

2.2 Parametric Cubic Models

Coon's (u,v) notation was not used for parametric cubic coordinates because the indicial notation, $\mathbf{z}\ (\xi_i)$, made the tensor product equations for elastic energy easier to implement for solids on the Navy project. We used three different but mathematically equivalent formats for parametric cubic curves: (1) Algebraic in which the coefficients of ξ^k are given for $0 \leq k \leq 3$, (2) Geometric in which the value of $Z\ (\xi)$ and the parametric derivative $Z_{,\xi}$ are given at the two end points ($\xi = 0$, $\xi = 1$) and (3) Point in which the value of $Z\ (\xi)$ is given at the one-third points ($\xi = 0$, $\xi = 1/3$, $\xi = 2/3$, $\xi = 1$). The symbols used for

these three different format polynomial coefficients are S, B, and P and the summation convention for repeated indices is adopted for i = 1 to 4.

Algebraic $Z(\xi) = H_i^{S}(\xi) \cdot S_i$

Geometric $Z(\xi) = H_i^{B}(\xi) \cdot B_i$

Point $Z(\xi) = H_i^{P}(\xi) \cdot P_i$

There are many other Point formats possible. NASA Patran used four Gaussian quadrature points for interpolatory quadrature calculations instead of the one-third points. Equations for $H_i^{S}(\xi)$, $H_i^{B}(\xi)$ and $H_i^{P}(\xi)$ are provided in the Navy report. The purpose for putting these equations in the monograph is to provide a context for the hyperpatch definition and not for the derivation of mathematical properties. The Navy contract report for the project cited in the Bibliography has those details.

Early hyperpatch solid modeling was called Analytic Solid Modeling (ASM) by PDA and hyperpatches are still available in MSC.Patran. The first geometry intersection algorithms for ASM Boolean operations were based in part on Hank Timmer's work for NASA Ames. Year's later more efficient solid modeling kernels like Parasolid that use Boolean operations on their five primitive shapes (block, cylinder, cone, sphere, and torus) were added. The Parasolid kernel is used by many CAD geometry systems in industry. A mathematician and good friend, Mac Casale, wrote the first versions of ASM and later interfaced ASM with the Parasolid kernel.

Hermite cubic curves

The linear transformations that map one set of coefficients into another can all be determined from two small coefficient matrices, $S_i = [\ N_{ij}\ ]\ P_j$ and $S_i = [\ M_{ij}\ ]\ B_j$ whose matrix coefficients are defined in the 1974 Navy report. Blending of two Hermite curves occurs when the curves are given the same tangent vectors at their connecting end points. Blending allows the ASM modeler to chain spatial curves for slope continuity in a geometry model, as in a helix for example. Conversely, one Hermite curve can be subdivided to create any number of beam elements in a finite element model.

Product geometry models almost always have similar scales for the "x,y,z" coordinates. However, if a curve has coordinates that differ by many orders of magnitude, like a stress-strain curve, then they should be scaled before blending to avoid artifacts. Such models are not recommended but customers sometimes use software in very unusual and unexpected ways.

Hermite-Coons bicubic surface patches

Each coordinate function for a bicubic Coon's surface patch $Z_i(\xi_1, \xi_2)$ can also be written in algebraic, geometric or point format. The surface patch formats require 16 coefficients for each coordinate function. The Geometric format has four parameters at each of the four corners,

$$Z_i\ ,\ Z_{i\ ,\ \xi_1}\ ,\ Z_{i\ ,\ \xi_2}\ ,\ Z_{i\ ,\ \xi_1 \xi_2} \qquad i = 1,2$$

and equal cross derivatives at two corners insure slope continuity across the common edge between adjacent patches. These B_{ij} can be created by construction if the patch is for an analytic surface like a saddle shape. If not they can be computed from the P_{ij} or S_{ij} if the patch was created in one of the other formats.

Algebraic $$Z(\xi_1, \xi_2) = H_i^{S}(\xi_1)\, H_j^{S}(\xi_2) \bullet S_{ij}$$

Geometric $$Z(\xi_1, \xi_2) = H_i^{B}(\xi_1)\, H_j^{B}(\xi_2) \bullet B_{ij}$$

Point $$Z(\xi_1, \xi_2) = H_i^{P}(\xi_1)\, H_j^{P}(\xi_2) \bullet P_{ij}$$

The B_{ij} and P_{ij} patch parameters are defined in the Navy report but the S_{ij} are not because they require up to 16 terms for each coefficient. They can be computed using the following linear transformations,

$$[\, S_{ij} \,] = [\, M_{ik}\, B_{kl}\, S_{jl} \,] = [\, M \,]\,[\, B \,]\,[\, M \,]^T$$

$$= [\, N_{ik}\, P_{kl}\, N_{jl} \,] = [\, N \,]\,[\, P \,]\,[\, N \,]^T$$

Hermite-Patran tricubic hyperpatches

Each coordinate function of a hyperpatch $Z_i(\xi_1, \xi_2, \xi_3)$ can be written in algebraic, geometric and point formats too. The notation while simple now starts to be cumbersome to describe in detail because of the triple indices that occur. We use a contracted notation here that helps simplify the code for doing the transformations

Algebraic $Z(\xi_1, \xi_2, \xi_3) = H_i^S(\xi_1)\, H_j^S(\xi_2)\, H_k^S(\xi_3) \bullet S_{ijk}$

Geometric $Z(\xi_1, \xi_2, \xi_3) = H_i^B(\xi_1)\, H_j^B(\xi_2)\, H_k^B(\xi_3) \bullet B_{ijk}$

Point $Z(\xi_1, \xi_2, \xi_3) = H_i^P(\xi_1)\, H_j^P(\xi_2)\, H_k^P(\xi_3) \bullet P_{ijk}$

The sixty-four hyperpatch parameters can be written as four sets of sixteen coefficients by suppressing any one of the three parametric coefficients and here ξ_3 is made the contracted coordinate. A hyperpatch is then defined by the four bicubic patches at $\xi_3 = 0$, 1/3, 2/3, and 1. Like a solid laminate made from four ply's the hyperpatch is constructed from four surface patches B_k for k = 1 to 4 in contracted notation as $[\ \beta\ (\xi_3)\ ] = H_k^B(\xi_3)\ [\ B_k\ ]$ where,

$[\ B_1\ ] =[\ B_{ij1}\ ]\ ,[\ B_2\ ] = [\ B_{ij2}\ ]\ ,[\ B_3\ ] = [\ B_{ij3}\ ]\ ,\ [\ B_4\ ] =[\ B_{ij4}\ ].$

Transforming a hyperpatch from point to geometric format is reduced to just four patch transformations,

$$[\ B_k\ ] = [\ [\ F\ ]^{-1}\ ]\ \ [\ [\ F\ ]^{-1}\ [\ P_k\ ]\ [\ [\ F\ ]^{-1}\ ]^T\ ]$$

where $[\ F\ ]^{-1} = [\ M\ ]^{-1}\ [\ N\ ]$. This is the efficient form of the transformation equations used for calculations.

2.3 Geometry Model Construction

NASA Patran was developed before modern operating systems like Windows and at a time when interactive graphics was pretty basic. Before efficient point-and-click menus, Patran-G geometry commands had to be typed in from a keyboard that was sometimes just a DEC VT 100 terminal. Our first color graphics device could be toggled back and for forth between text and graphics modes during a Patran-G session. We also had to interface Patran-G to customer devices that digitized geometry data from paper drawings in those early years.

Construction-In-Context

The basic idea of construction-in-context is very simple; data from any operation can be referenced by other operations before the data are available. NASA Patran implemented this using a queuing algorithm to determine the execution sequence during a session. This enabled batch processing of session files. Here we are talking about the Phase 1 geometry data generator. The first construction operations available for lines (curves), surfaces and solids were limited. PDA was working on a very small budget and with a very small team. We first had to demonstrate that Phase 1 could create industrial strength solid geometry models and then in Phase 2 “FEG” the geometry models and output a Nastran Bulk Data File (BDF) for FEA. In the syntax of Phase 2 of NASA Patran “FEG” was a verb meaning to generate finite element data for a Nastran analysis of the FEM model. We later added FEA output for ANSYS and many other applications to PATRAN-G.

NASA Patran had 24 geometry construction operations plus MSCALE, which moved and scaled a group of lines, patches and/or hyperpatches. A few operations are described in the Appendix with the actual construction commands. By 1983 in Release 1.5 of Patran-G the number had grown to over 135 operations. It was the first really robust release in my opinion. Neil Harrington was the release manager, chief programmer and second shift test engineer. After that 1.5 Release the team grew rapidly to over 25 people by 1984 giving Neil some much needed help. The first few years after Patran-G Release 1.0 were chaotic. Adding software engineers to PDA caused both culture shock and excitement. PDA was entirely owned by the employees and none of us owned more than about 10% at the time of the IPO in 1985.

A Stanford Professor, Jim Clarke the founder of SGI, came to visit PDA around that time and sat in on a design review of our PATRAN-G graphics software. The young developer making that presentation didn’t know who he was and kept interrupting him to say that Jim just did not understand computer graphics. This was one of many anecdotes from that period that helps to describe the kind of semi-rationale exuberance associated with rapid growth. Business is booming and everyone, at least in private, is convinced he or she knows more about (pick a topic) than anyone else on the planet. Risks and rewards were both growing rapidly and the distributed computing market was exploding. DEC for one had problems with those explosive market changes and the associated market risks as did other minicomputer companies and also PDA Engineering.

By Patran II in 1985 the solid modeling module had added Boolean operations that were called Conceptual Solid Modeling (CSM) for a while. A big advance but CSM was still a keyboard command driven system and it was clear that something needed to be done to improve Construction-In-Context. About that time Andy Astor created a Patran Command Language, PCL, which could be used by application engineers to create macros.

Andy was a brilliant young computer scientist. His initial design has continued to grow and has been used to write countless Patran PCL macros that help customers automate the construction of large models. That early system has undergone many changes and a few name changes but I still call it PCL. Now it might be considered the API for Patran customers and partners.

Today full vehicle models are often created from just PCL macros and old FEM models at several automotive companies. To give you some idea of how large models have become, a 2006 performance benchmark model for the German auto industry of only one MSC.Nastran engine model had 25 million degrees of freedom. Even more impressive to me was the fact that the benchmark was for the eigenvalues of the 3D engine model.

3. Hermite Finite Element Models – FEA

First generation NASA Patran software decoupled geometry and meshing. Later the introduction of interactive graphics and menu driven windows coupled the engineer in real time to the modeling process. That made FEM much faster and much less error prone. An engineer could view and edit a model interactively during its construction. This had a huge impact on productivity and that helped enable virtual product development. CAD and CAE applications were first at the component level and later scaled up to assemblies of the entire vehicle that today allow virtual performance testing of a new design. At GM they ran 10000 car crash simulations every month allowing them to explore joining methods as well as chassis design shapes.

However, in the 1980's computers were still pretty slow and applications stayed mostly at the component or substructure level for a few more years. This portion of the Chronicles can be skipped if you are only interested in geometry modeling of product shape for FEM and not in the use of hyperpatchs to generate stiffness matrices for FEA. The principal difference is that FEA requires modeling material geometry and physical properties that vary inside 3D composite materials and structures. These properties are needed to integrate the potential energy equations over each finite element volume to form stiffness matrices. This is especially true for an involute composite construction used for carbon-carbon rocket nozzles. To keep meshing independent of material geometry these data were created from the ply pattern data used to manufacture the composite. A PDA engineer, Jody Hart, wrote his UCLA Ph.D. thesis on this topic and we used similar math models to design ply patterns for many space motor rocket nozzles. These models allowed concurrent design and manufacturing simulations that produced nozzle designs with greatly reduced manufacturing risk.

3.1 Hyperpatch Finite Elements

The Navy hyperpatch finite element for 3D composites had 64 nodes per element, a lot more than most other solid elements. The finite element's interior nodes made it possible to resolve both the large fiber dominated stresses and the much smaller interlaminar stresses without making simplifying assumptions. We were concerned that any deformation assumption would mask or distort the interlaminar stresses. Poorly understood composite design edge effects were

causing delaminations much below service load levels. Nick Pagano and Byron Pipes had begun to analyze these stresses in thesis research projects but aircraft designers needed better 3D FEA tools to simulate delamination failures in actual attachments.

The large size of the 192x192 Hermite finite element stiffness matrix required partitioning the element matrix into 64x64 submatrices to run on the small memory computers of that era. Even Nastran, which has always had great algorithms for solving large sparse matrix equations, was slow to solve these not so sparse matrix equations created using hyperpatch finite elements. At one point we even used a scaled Conjugate Gradient (CG) algorithm from my thesis to solve the equations by direct energy minimization methods. In that approach the stiffness matrix for the structure is not assembled. The method computes the potential energy function and its gradient element-by-element. At each step of the CG algorithm a connectivity map distributes displacements to each finite element from the assembled displacement vector. Individual element gradients are computed and then mapped back to create an assembled load vector by reversing the process. This allowed us to compute a new conjugate direction for the next CG step without an assembled stiffness matrix. I am getting off track again, back to the hyperpatch finite element.

3.2 Hyperpatch Material Geometry

In Nature objects have finite geometries for both the object and for the material from which the object is made. Engineering materials contain atoms assembled in various repeating volume elements (RVE’s) that are

classified by NIST as either polymeric, metallic, ceramic or a composite of these three material classes. In continuum mechanics the material elastic properties are usually assumed to be constant in a rectangular, cylindrical or spherical material frame. In the case of composites made using involute construction this assumption breaks down because the material frame is a field that varies inside the object by design. This variation causes the elastic properties to vary spatially in rectangular, cylindrical and spherical coordinates. That variability presented finite element modelers with a challenge that was poorly understood in the 1980's. Designers were using involute construction to make nozzle components and stress analysts were using cylindrical frame constant material property models. Their results were wrong and often significantly wrong.

Nick Pagano at the Air Force Materials Lab and others studied the geometry and developed involute material models for stress analyses. At PDA we extended these models to ply pattern design and Tom Kipp created a software tool for designing low risk involute composite structures. We used the hyperpatch finite element to link involute nozzle design and analysis applications for the Air Force Rocket Propulsion Lab (AFRPL). Joe Hildreth managed the project for the lab and that software took a couple of years to complete. We used Euler angle distribution functions to orient the involute composite material frame at interior points of the hyperpatch finite element. The AFRPL work was summarized in a 1985 AAIA Journal article.

There was just one problem with using variable material geometry frame fields; Patran had no Field entity. In the case of FEM material geometry, big customer projects

needing new Patran features and functions were beginning to collide with demand from many different customer applications for the same scarce resources that PDA projects needed. In this instance we did add a Patran scalar Field directive in the 1985 release of Patran II that was used for Euler angle fields and many other scalar data fields like temperature and pressure. It was one of many business situations caused by rapid growth that began to tax our ability to manage growth. The pressure to support every new Workstation and new Graphics device was a much bigger problem and we started to have "too much happiness" crises that seriously stressed our team. We were evolving rapidly.

Years later we embedded the variable Euler angle modeling capability in MSC.Nastran where it can be used to orient variable material geometry fields for ordinary constant property finite elements. This was used to decouple the material geometry from the finite element mesh for a simple involute composite cylinder. The MSC.Nastran feature added fields to a coordinate function option and like early Patran data hyperpatch models both use spatial fields to define Euler angles in a reference coordinate frame. The FEM modeler, here Patran, must represent both finite element objects and infinite domain fields for scalar and vector fields. It is possible to create fields in the FEA solver but this is not the best architecture because they are then late binding to the FEM model.

3.3 Data Hyperpatches and Change

Returning to the hyperpatch chronicles, we created data hyperpatches in early NASA Patran to model spatial

properties data for Nastran finite elements. This was in the 1978 version developed for NASA. It was considered scary stuff at the time by many Nastran users and was never especially popular. I liked it of course and used it for P/COMPOSITE, a 3D hyperpatch finite element code that PDA and several aerospace customers used to design and analyze high temperature carbon-carbon structures. P/COMPOSITE used data hyperpatches with up to 21 components to model high temperature anisotropic materials. This was an important application for PDA design projects but not for most Patran-G customers. Data hyperpatches marked an emerging boundary between our original prototype development business and our new software business. Patran release change control procedures were painful but absolutely necessary now and we had to accept that discipline. PDA suddenly had hundreds of Patran customers worldwide depending on timely new releases and their business requirements quickly took priority.

4. Composite Design and Analysis at PDA

The 1980's were a period when exotic carbon-carbon composite materials were being used on rocket motor development projects. The characters in the story then included PDA engineers like Greg Crose, Tom Mack, Dick Haddock, Tom Kipp and others who used Patran-G and FEA codes on a regular basis for mechanical and thermal applications. They were not only early Patran adopters they were defacto members of the Patran-G development team. PDA customer teams also had remarkable engineers like H. O. Davis at Aerojet, Frank Inman at Thiokol and George Lucido at Kaiser who contributed greatly to our understanding of the

processing chemistry and manufacturing skills needed to make simulation-based design work on large aerospace composite manufacturing projects. As I said in the introduction, collaboration among individuals and organizations is a big part of the story. PDA was heavily involved in cold war projects that kept early Patran at the cutting edge of simulation technology for years.

4.1 Composite Material Applications

Many customer projects in the 1980's struggled with carbon-carbon failures in processing that put more than the assumptions of classical lamination theory in question. There were several high temperature carbon-carbon applications that desperately needed design solutions not more failure analyses. Several build-test-fix cycles had exhausted budgets, schedules and three manufacturing companies best efforts without finding a solution. Finally one of the companies and PDA were given a chance to try a simulation-based design approach to concurrently reduce design and processing risks. That project brought ply pattern designers, materials scientists, test labs and manufactures together in a remarkable collaboration that found a solution. This chapter tells that story and similar design analysis collaboration stories. They provide case studies of the role hyperpatch finite element technology played in bridging the gap between designers, analysts and manufacturing engineers. They also provide insight into the way FEM technology applications enabled PDA to become a global software business. The business skills we had and the new software business skills we needed were very different to say the least. The IPSM-II story is mostly about how FEM geometry tools enabled

concurrent engineering and how PDA began to learn to do what I like to call innovation-in-context.

IPSM-II Nozzle Design Collaboration

In 1983 Morton Thiokol ran a successful improved performance space motor (IPSM) test series that used involute nozzle components designed by PDA using hyperpatch finite elements. They were kind enough to let us use a photo from the first IPSM-II test in our 1984 Annual Report and in the 1985 PDA Engineering IPO Prospectus. In fact it was featured prominently on the inside back cover of the IPO Prospectus. ISPM-II and other composite design application stories are recounted here in a way that hopefully will be useful as case study material for concurrent engineering design education programs.

3D Carbon-Carbon Material Testing

PDA was selected to design the IPSM-II nozzle exit cones because of the earlier successful collaboration with Aerojet and the Air Force Rocket Propulsion lab in solving carbon-carbon nozzle processing problems just mentioned. In general terms the technical solution included an innovation in ply pattern design, an investment in a large 3D carbon-carbon material test program at the Southern Research Institute (SoRI) and a better understanding of nonlinear shear behavior. SoRI did most of the carbon-carbon material testing at high temperatures in those days and they were very helpful. PDA designed specimens for the triaxial test matrix that measured the 3D carbon-carbon properties we needed for simulation-based design.

We validated the 3D material properties for computer simulations using sub-element structural tests. This was expensive but necessary to avoid any assumptions about 3D composite material behavior. Our material model was in effect the SoRI test data not a set of parameters for a theoretical graphitic material model. As it turned out the nonlinear behavior of laminated carbon-carbon was bi-modular in shear. This was something we had not expected. Most graphitic materials have symmetric shear behavior in the plane. As shown in our 1978 AIAA Journal paper, warp-fill nonlinear shear behavior for a fabric-based material was not the same as nonlinear fill-warp shear behavior. This gets back to an earlier comment that actual as well as virtual testing are both necessary to make simulation based design work. It is especially true in high temperature composite design projects.

Concurrent Nozzle and Pattern Design

Ply pattern design was something the manufacturer normally did and it took them a long time to design patterns on drafting boards. Involute solid geometry is complex. Each ply spirals from the inside surface of the nozzle to the outside and the only geometry that does this with constant thickness plies is an involute. When the nozzle is a simple cone shape, this can be done without fabric distortion but most nozzles including the IPSM-II forward cone have some curvature as well as other structural geometry details. These details made ply pattern design difficult and slow. Most designers assumed one edge of the pattern was straight to make board design work easier. Unfortunately this practice caused problems in manufacturing including internal wrinkles and ply slippage during lamination and cure.

PDA created a new digital geometry tool without any straight edge assumptions. The software tool allowed us to create dozens of patterns in the time it took to create one feasible design on a drafting board. It also allowed us to analyze billet processing stresses and nozzle performance for dozens of virtual ply pattern designs. Digital patterns and Monte Carlo methods allowed us to quickly find patterns that reduced fabric distortion, which reduced lay-up problems in the shop. The end result was involute carbon-carbon nozzle components with low manufacturing risk and reliable performance. That was evident in the successful IPSM-II space motor firing photographed by Morton Thiokol. It was a case study in concurrent product and process design with a happy ending for the customer.

Innovation-in-Context

The story to this point sounds like a textbook case of immaculate conception engineering. It begins with a problem statement, introduces innovative new technology, talks about collaboration among the interested parties, and a solution appears with no problems and no worries. That's not how it happened. All of the interested parties were very skeptical and some demanded to be shown why our new design method was any better than the old one. Manufacturers especially have a natural suspicion of research and development people of any stripe. PDA was no exception to this healthy hostility.

We flew monthly shuttles to a manufacturer in Oakland to work in their factory at each stage of the design build process. I was there so often the shop steward thought I worked there. The practice of engineering sometimes requires leaving the air-conditioned office and getting involved in the build process at the shop traveler level. We collaborated with engineers at each manufacturing company involved in making exit cones for IPSM-II to insure our digital designs could be implemented using their company's prepregs and processes. That meant adding checks to the shop traveler for prepreg tolerances at specific processing stages. We also worked with QA inspectors on the first article to interpret design intent when the level of detail was inadequate. Should the pattern be formed sunny side up? It can make a difference for some fabric weaves and we had not specified that detail for example.

Innovation-in-context is my way of saying that the practice of engineering cannot always be decoupled into completely autonomous supply chain activities when composite material changes are being made. In this case we needed to work with the whole supply chain executing the changes. That is the main point of the IPSM-II story. If we had mailed our new nozzle pattern design to Morton Thiokol and stayed at home running computer simulations this story would very likely not have had a happy ending.

Business Context

Most composite design projects are not like IPSM-II. It was for a new space motor that put expensive satellites into orbit. GPS and other satellites often cost well over $100M each and can take years to build. The motor was single use and the project could afford expensive material tests to insure valid computer simulations to reduce the risk of failure to an absolute minimum. This

carbon-carbon composite design was for a small but high margin aerospace niche market. Mass markets like automotive require decoupling tasks so that multiple manufactures in a supply chain can make parts to industry standards. PDA was evolving as a company and learning to serve both old customers in our high margin niche markets and new Patran-G customers who were usually in mass markets like automotive.

4.2 Composite Structural Applications

Another reoccurring composite design problem in the 1980's was the warping of structures during autoclave cure. PDA worked on several warping problems for the Air Force Logistic Command (ALC) responsible for maintaining, repairing and sometimes redesigning structures that use composites on military aircraft. Just as the lack of early digital geometry tools limited FEA applications for structures, the lack of digital composite materials data was limiting the usefulness of FEA for composite structures. Our first task for Milt Swope and Steve Nolet at the McClellan ALC Advanced Composites Program Office in Sacramento was to develop an Advanced Materials Database System (AMDBS). We needed software that directly connected composite material test data and metadata to CAE applications. The design of AMDBS was done in collaboration with ASTM Committee E49 then headed by John Rumble of NIST and the Automotive Composites Consortium (ACC) especially Carl Johnson (Ford) and Tom Dearlove (GM). The ACC used a mix of ASTM and AAC standards for property testing of composite materials. ACC test procedures also required test results to be reported as digital data using a spreadsheet format they provided.

PDA worked on several ALC composite design projects at centers around the country. We were part of an ALC basic ordering agreement managed by Battelle Memorial Institute in Columbus, Ohio. Battelle also published MIL-HDBK 5 and 17 for the military and we later became their partners in developing MIL-HDBK material databases. Among the Battelle projects for the ALC was the redesign of an aircraft main landing gear door to change the structure from metal to composite. The door aerodynamic shape had compound curvature, which is almost always difficult to cure without warping.

C-141b Aircraft Composite Door Prototype

The C-141 is a large old transport aircraft made from lightweight aluminum with lots of honeycomb structure. After years in service these planes tended to have water ingression in many of the honeycomb parts. We were told it was enough water to impact takeoff weight on occasion and the ALC wanted a prototype composite part redesign to test. One C141b main landing gear pod had a life raft door with over fifty pounds of water in it. That door was also hard to maintain because of water ingression damage. Dave Felker did the baseline redesign of the door at Robins AFB and PDA was given the job of designing a composite lay-up that would not warp. We also had to build a composite prototype door for the ALC to test, all on a very limited budget.

Original Equipment Design Information

Redesign of an old structural component ideally needs drawings, tooling, bills of materials and old design load information. Lockheed designed the C141 in the 1960's on drafting boards and it was later redesigned to have a longer fuselage in the C-141b. We were fortunate to find the loft lines for the C-141b main landing gear pod. We were not as lucky with design loads. Vintage design Information and tooling can be very hard to track down given organizational and technology changes that happen over a long period of time. Welcome to the ALC. Having geometry modeling capability in Patran was very helpful on this project. CAD geometry would have been nice if available but at PDA Ernie Julian was able to use the loft lines to design tooling for the door lay-up surface. He did it on the last drafting board at PDA.

Concurrent Structure and Stiffener Design

The ALC supplied us with a Nastran bulk data file (BDF) for Felker's baseline composite door redesign. It is remarkable how often a redesign project starts with a BDF file. The composite design used a triple X stiffener pattern that was a challenge to make. Lay-up tooling and cutting templates were checked using photographs taken at the manufacturer, C-CAT, in Fort Worth, TX. They had worked with PDA on the design of several carbon-carbon components that usually begin as a cured polymer matrix composite like the C-141b door. C-CAT made the first door using the ALC baseline design and it warped during cure cycle cool down as we had predicted. The challenge was to concurrently redesign the stiffener and the door skin lay-ups without materially changing the baseline structure. We could not change the bill of materials or the baseline tooling on this project.

Simulation Context

We used a 3D hyperpatch finite element model to analyze cure cycle shrinkage deformations of the baseline design because the stiffeners were so thick. They were about 50 plies with multiple foam core inserts. Tom Mack, John Norman and I struggled with this model because of the multiple core nature of the baseline stiffeners design. We each had our personal expert opinion about how the lay-up should be changed and they all failed in redesign simulations. With time and money running out we resorted to Monte Carlo like runs until John Norman found a solution. The key was where to locate the foam core inserts in the triple X stiffeners. The result was a door with very little warping and even that was in the right direction. When the door was shut it latched tight and the aerodynamic surface was clean. The simulation context here was not for a new aircraft but the redesign and repair of a structure on an existing aircraft in service for many years. This was a new market for PDA at that time and we expected that the need for advanced composite design services would continue to grow which they did for a while. Then the cold war ended.

Business Context

At the end of the cold war PDA's R&D work for the DoD was being cut as it was for every other defense contractor. We knew that change was coming and had begun to shift our DoD focus to include the ALC. They were growing their composite material applications as planes like the F-22 were being designed with ALC input. After the huge cost overruns on the B2 and other stealth aircraft, composite design process changes were being made. ALC projects gave us the opportunity to design database software linking composite material test data and metadata to CAE. That technology enhanced our CAE portfolio and started us thinking about simulation data management for aircraft and other capital equipment projects. The AMDBS project eventually led to a new software product, Mvision, and to a new object oriented database system for Patran. We looked to services projects as a way to learn from customers about their needs. Many new product decisions at PDA had their origins in the solution of a customer application problem. However, the synergy between our DoD projects and our rapidly growing software business was starting to wear thin.

Satellite Composite Space Structure

This 1986 application story did not have a happy ending. We were able to diagnose the basic reason for the warping failure during cure but we did not find a design solution in the time and budget available. At that time composite designs almost always started with a balanced lay-up. However, in this case we found it was part of the problem and that was as far as we got before the project was over. Years later after a serious health problem I had time to reflect on many things and this failure was one of them. In the intervening years Boeing and MSC had developed a stochastic software tool that Greg Crose and I used to continue the search for a lay-up that would not warp. That search did have a happy ending and it provides a nice segue way into stochastic design methods.

1986 Composite Design Application

The 1986 study was of cure cycle warping in struts for a satellite space structure. The manufacturer made the struts from unidirectional prepreg tape wound around a foam core. The core was rectangular in cross-section with rounded corners. A 1987 AAIA paper has a schematic of the graphite-epoxy strut showing the layup with thickness exaggerated. The manufacturer's expectation was that a balanced laminate design would not twist (warp) during cure cycle cool down. The struts not only twisted, some had matrix microcracking as well. The composite was a lightweight thin walled structure and it was very stiff. Assembly in space to form a truss structure required the struts to fit into connector joints. Any twisting during cool down made the struts unfit for assembly in space. PDA's study was documented in a 1987 AIAA paper Tom Mack and I wrote and the composite property data from that paper were used in the new search for a lay-up that would not twist during manufacture.

Stochastic Design Methods

In 1994 Rocketdyne won a five-year DARPA contract to develop a Robust Design Computational System (RDCS). Computers and local area networks were finally getting powerful enough to use Monte Carlo design scan methods in multidisciplinary finite element applications. Glenn Havskjold and Raj Rajagopal were the Rocketdyne team leaders and PDA was the commercialization house for the project. The other members of the team were Ford and McDonnell Douglas. Early in the program Boeing acquired both Rocketdyne and McDonnell Douglas and about that time MSC acquired PDA Engineering. The RDCS project became a robust design activity in every sense of the word. In spite all these organizational changes Glenn, Raj and their team completed RDCS and delivered the code to MSC for beta testing in 1999. Their vision for RDCS was a network software tool that would let engineers anticipate and prevent design errors before hard decisions like configuration, materials and tooling had to be made. These are the so-called long lead-time commitments that once made cannot be materially changed without large cost overruns.

Lets begin with the simulation context. At Rocketdyne high risk space motors were getting even riskier as payloads grew and factor-of-safety methods began to break down. Orbital payload costs were hurting space programs in Congress and of course the Challenger disaster had put the whole Space Station program on indefinite hold. At Ford Motor crash test costs were making build-test-fix methods unaffordable and simulated crash tests took too long with their then current computer infrastructure. Ford's early interest in RDCS was the software that networked workstations and allowed hundreds of FEA runs to be made overnight on idle machines. MSC was of course also interested in software that could increase customer use of FEA by an order of magnitude. My interest was more personal. Harry Meriwether had introduced me to Monte Carlo methods years earlier and I thought RDCS might be the tool that would let us use stochastic design search methods to solve the 1986 space strut warping problem and other material geometry design problems.

Innovation in Context

When we first approached the problem we reasoned that if the strut twisted clockwise it could just as well twist counter-clockwise with another layup. If that were true then a zero twist design must exist. That turned out to be true but in searching for that layup we found there were many zero twist layups and some had side effects worse than twisting. One of the zero twist layups had a picture frame shear deformation (racking) that reminded us once again that unintended side effects do happen. Using Monte Carlo methods we had found many zero twist designs but a solution was yet another step away. However, the Monte Carlo simulations also provided us sensitivity data and Pareto charts which helped us find a design without side effects. Unfortunately that design was very sensitive to small angle changes in the layup. In other words the perfect design was itself imperfection sensitive. At this point we became concerned that with normal tolerance settings on the winding machine the strut might still have high scrap rates.

To test the design for winding tolerance problems we again used Monte Carlo simulations but this time to do a tolerance analysis. The approach we took is similar to the approach Skip Creveling describes in his 1996 book, Tolerance Design. He and others used Monte Carlo simulations at Kodak to design tolerances for complex mechanical assemblies with many moving parts.

Here the need to control twist to a tight tolerance over several meters led to a unit twist tolerance of ± 0.1 mrad for our unit length model. The question was could it be done with realistic layup tolerances. At PDA we normally used ± 0.5 deg as a layup tolerance for filament winding. Monte Carlo simulations using that value for winding variability produced a twist standard deviation of 0.07 mrad and that made me uncomfortable. If we had it to do over I would have recommended changing from a unidirectional tape to a bias fabric material to provide the required torsional stiffness and strength for the strut. In composite design there are many ways to trade off product and process risks to meet design requirements. Analyzing composite design and processing tradeoffs is part of engineering practice and here stochastic methods would have been helpful.

Design Education Context

At UCI when I gave a lecture on tolerance design to a CAE class most students were very uncomfortable with the topic. Come to think of it many practicing engineers are too. Specifying tolerances and make-up torques for composites is not trivial. The level of detail at which product and process tradeoffs are taught at Universities is dependent on the University and many keep the focus at the systems level. In practice very few engineers become system designers. In my opinion students also need to be exposed to the topic at a level much closer to the practice of engineering in industry. This is especially true for later project management roles that many engineers will assume during their career.

Business Context

In summarizing these PDA case studies there is a noticeable shift from designing actual prototype composite structures to providing virtual product design services. As the business of PDA became increasingly software products and services we had to rapidly evolve and take on new roles often in new industries. This scale up had all kinds of risks when the business became global in the very first year after the IPO. It was a happy problem to have but nonetheless a

very difficult one and we had growing pains that would last for years. There were several CEO changes and we nearly went out of business at one point when our stock price fell to around a dollar.

5.0 Next Generation Design Applications

PDA's rapid growth brought changes and among them was my being assigned to a management role. Sadly my time as a practicing engineer was about over. Advanced products and new business development jobs at PDA and later MSC kept me traveling around the globe for more than a decade until cancer abruptly changed my life again. In those years on the road I never lost interest in hyperpatches or finite element models and suddenly fate gave me the chance to think about future applications. The company had grown with the CAE market, which had become an essential part of the design-build process at most customer sites. That expanded role for CAE was now IT critical and we had to develop information management tools for simulation data much as CAD companies had done a few years earlier for CAD product data management. That's important technology but it is not the focus here. This monograph continues to be about modeling and simulation technology and its relevance to new market design applications including molecular material models and even financial portfolio design scans.

Next generation finite element simulations could have been scale limited for micro-electro-mechanical systems (MEMS) applications. That would have been the case if accurate finite element models for micro-mechanics simulations were more expensive than physical testing.

Over night prototypes from a chip foundry make testing actual MEMS designs a practical option in industry. That fear went away rather quickly and the MEMS market, now in the billions, includes FEA design simulations. ANSYS for one has attracted attention with its MEMS analysis applications using FEA. Nano-electro-mechanical systems (NEMS) are a few years behind MEMS but carbon fullerenes and nanotubes are showing up in material products today, and nanostructures are also analyzed using FEA simulations for NEMS designs.

Hyperpatch Models for Nanomaterials

The similarity of hyperpatch models to DNA genetic molecular models has long been a fascination of mine. It could yield an information technology that impacts design at all scales and in many industries. New nanocomposite materials and molecular biomedical applications are in almost every issue of Nature, which is published weekly. UCLA oncologists tell me new chemotherapy drugs based on designer molecules are being discovered almost monthly and could lead to chemotherapy without massive collateral damage for many cancer patients. Even cancer specific vaccines are being tested today.

At the risk of being out of my element, I want to talk about information models for nano scale objects and suggest similarities between the taxonomy of finite element primitives and nature's amino acid primitives. The topic began creeping into the story with carbon isomer FEM models for fullerenes and nanotubes. The issue for me was, could a finite element model represent both a nano-scale equivalent continuum model and its

molecular mechanics model in the same application? In other words a hybrid model that bridges between the two. A little background here may be helpful. In 1944 Erwin Schrödinger wrote a monograph, “What is Life”, and asked himself why are atoms so small and could life be based on the laws of (quantum) physics and chemistry. In analyzing the questions he came to the conclusion that heredity material must be molecular and must be able to produce “order-from-order” using some then unknown code. His piercing analysis was first presented in lectures at Trinity College in Dublin and helped inspire Francis Crick who later co-discovered the genetic code, DNA, and its double helix structure. Francis Crick was also a physicist like Schrödinger. The genetic code is constructed from the four DNA molecules (A, C, G, T) in 64 ordered triples. That is 4x4x4 or 64 objects called codons. My fascination was that 64 ordered objects, xyz points, in space, also define the hyperpatch. For years that was as far as I got in connecting the two taxonomies.

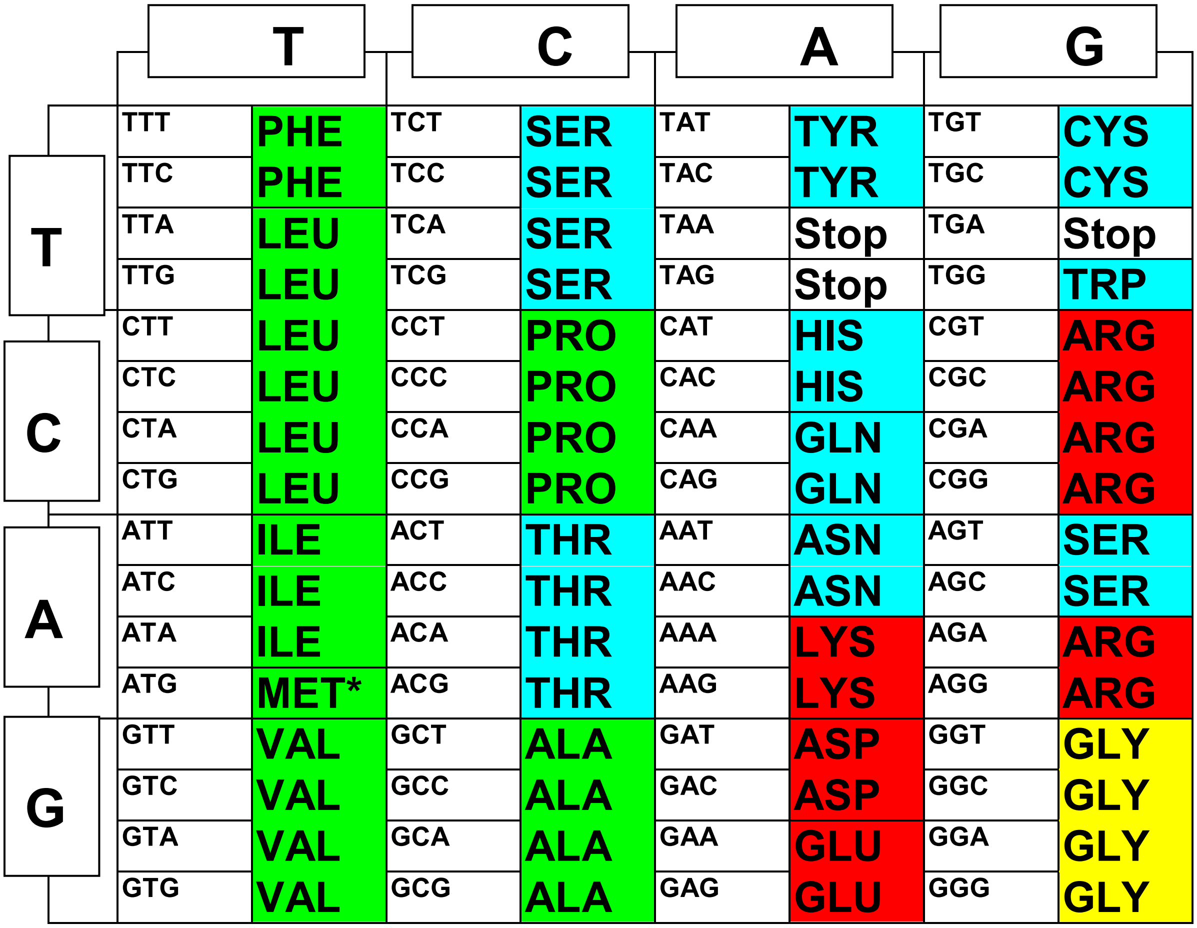
The first progress at connecting these two information models was in a 2003 NAFEMS paper and starts with a simple observation. Each model creates material objects from their four respective primitives; the nucleotides A, C, G, T for DNA and exponents C, Q, L, Z for the cubic Hermite polynomials in algebraic format. The genetic code links each of the 64 codons to one of just 20 genetic amino acids. These are the building blocks of virtually all biomaterials. The hyperpatch links each of its 64 “codons” to one of the 20 finite element geometry objects created from a regular hyperpatch. These are the building blocks for finite element material objects. In hyperpatch models, the primitives have only four possible base pairs because nodal end points and

slopes must connect to nodal end points and slopes. The DNA schema also has only four possible base pairs, AT, TA, GC, and CG because DNA double helix strands are Watson-Crick complements of each other. At this level the taxonomies match closely. Can the 20 amino acids be related to the 20 hyperpatch "codons"? One part of the answer lies in combinatorial mathematics.

The number of combinations of 4 things taken 3 at a time with recurring elements counted once is (4+3-1)! / 3!(4+3-1-3)! = 20. That observation eluded me for years. While there are 20 amino acids three of the codons, TAA, TAG, and TCA are Stop signs that were not related to hyperpatch codons in the 2003 NAFEMS paper. That must be addressed in discussing the nature of the assembly process used to create biomaterials and engineered materials. Assembly involves RNA codons that actually "execute" the genetic code. You may have asked yourself at this point where is the Start sign? It is ATG, which also codes for the amino acid MET or methionine.

I am getting a little ahead of myself again. First we need to compare the taxonomy of the DNA genetic code and the hyperpatch FEM code. The graphics on pages 46 and 47 were patterned after those in the computational molecular biology literature. There are many sources and a 2000 textbook by USC Prof. Pavel A. Pevzner's is particularly well illustrated. He also introduces biology and algorithms simultaneously. A very nice touch for students young and old as the textbook focuses on algorithms for complex simulations. His textbook graphics also illustrate both the algorithms and their application to DNA simulations.

Genetic DNA Code is Redundant
64 Codons map to just 20 Amino Acids and a Stop Sign



	T		C		A		G	
T	TTT	PHE	TCT	SER	TAT	TYR	TGT	CYS
	TTC	PHE	TCC	SER	TAC	TYR	TGC	CYS
	TTA	LEU	TCA	SER	TAA	Stop	TGA	Stop
	TTG	LEU	TCG	SER	TAG	Stop	TGG	TRP
C	CTT	LEU	CCT	PRO	CAT	HIS	CGT	ARG
	CTC	LEU	CCC	PRO	CAC	HIS	CGC	ARG
	CTA	LEU	CCA	PRO	CAA	GLN	CGA	ARG
	CTG	LEU	CCG	PRO	CAG	GLN	CGG	ARG
A	ATT	ILE	ACT	THR	AAT	ASN	AGT	SER
	ATC	ILE	ACC	THR	AAC	ASN	AGC	SER
	ATA	ILE	ACA	THR	AAA	LYS	AGA	ARG
	ATG	MET*	ACG	THR	AAG	LYS	AGG	ARG
G	GTT	VAL	GCT	ALA	GAT	ASP	GGT	GLY
	GTC	VAL	GCC	ALA	GAC	ASP	GGC	GLY
	GTA	VAL	GCA	ALA	GAA	GLU	GGA	GLY
	GTG	VAL	GCG	ALA	GAG	GLU	GGG	GLY

7 Hydrophobic Amino Acids 🟩

8 Polar Amino Acids 🟦

4 Charged Amino Acids 🟥

1 Non Chiral Amino Acid 🟨

20 Amino Acids

* ATG codes for MET or Start

Hyperpatch FEM Code is Redundant
64 Codons map to just 20 Finite Elements

	C		Q		L		Z	
C	CCC	HEX64	QCC	HEX48	LCC	HEX32	ZCC	QUAD16
	CCQ	HEX48	QCQ	HEX36	LCQ	HEX24	ZCQ	QUAD12
	CCL	HEX32	QCL	HEX24	LCL	HEX16	ZCL	QUAD8
	CCZ	QUAD16	QCZ	QUAD12	LCZ	QUAD8	ZCZ	LINE4
Q	CQC	HEX48	QQC	HEX36	LQC	HEX24	ZQC	QUAD12
	CQQ	HEX36	QQQ	HEX27	LQQ	HEX18	ZQQ	QUAD9
	CQL	HEX24	QQL	HEX18	LQL	HEX12	ZQL	QUAD6
	CQZ	QUAD12	QQZ	QUAD9	LQZ	QUAD6	ZQZ	LINE3
L	CLC	HEX32	QLC	HEX24	LLC	HEX16	ZLC	QUAD8
	CLQ	HEX24	QLQ	HEX18	LLQ	HEX12	ZLQ	QUAD6
	CLL	HEX16	QLL	HEX12	LLL	HEX8	ZLL	QUAD4
	CLZ	QUAD8	QLZ	QUAD6	LLZ	QUAD4	ZLZ	LINE2
Z	CZC	QUAD16	QZC	QUAD12	LZC	QUAD8	ZZC	LINE4
	CZQ	QUAD12	QZQ	QUAD9	LZQ	QUAD6	ZZQ	LINE3
	CZL	QUAD8	QZL	QUAD6	LZL	QUAD4	ZZL	LINE2
	CZZ	LINE4	QZZ	LINE3	LZZ	LINE2	ZZZ	POINT

10 Solid Elements	🟩
6 Surface Elements	🟦
3 Line Elements	🟥
1 Point Element	🟨

20 Finite Elements

Again, please note the FEM "codons" in the graphic refer to the algebraic format for Hermite polynomials. That would please Hermite but it is the geometric format that is used for assembly and it is in that format that FEM "codons" have only four possible base pairs. Also, there are no triangular or tetrahedral elements even though degenerate hypepatches will produce them. Nature does not collapse atoms into black holes when making biomaterials. However, here we begin to run into mixed metaphors because the hyperpatch can represent continuum material models as well as finite molecular material models. The question is can they represent both in one model and serve as a bridge? To keep our assumptions clear lets define them for each application.

Molecular Mechanics Models

In the 2003 NAFEMS paper was a molecular mechanics model of a C60 capped C(5,0) single walled nanotube. This type of model is based on the Born-Oppenheimer approximation of the Schrödinger equation. They take advantage of the fact neutrons are much heavier and move much slower than electrons. Thus molecular motion can be analyzed ignoring electrons. Energy associated with stretching, bending torsion, and elastic interactions can be calculated using a force field or using empirically defined beam finite element elastic constants. The FEM beam elements have no mass. The mass of each atom is lumped into point mass elements at the ends of beam elements. Details may be found in the NIH Guide to Molecular Modeling on the Web. I hasten to add that many have used similar finite element models for molecular mechanics analyses in recent years including NASA researchers.

Innovation-in-Context

A few comments about context may help to better connect taxonomy and simulation technology. Computational molecular biology is about algorithms for mapping, sorting, sequencing, comparing and basically reverse engineering human DNA. These simulations search for mutations that produce a specific disease like breast cancer. Pharmaceutical companies also use simulation of biomaterials and molecular processes in product design. Computational molecular mechanics in the chronicles is about designing and analyzing new nanocomposite materials, structures and processes. Both molecular material applications use Monte Carlo simulations and similar software tools for design, analysis and visualization of results. Both make nanoscale modeling of new materials more accessible to designers and analysts. These computer simulations increase productivity in organic and inorganic design applications.

Business Context

When your job is to manage a companies advanced technology portfolio you must answer “business case” questions from the CEO. Is there a market for this, is it compatible with our current technology base, how much and how long, when will we see the first revenue and what about margins? The story of Patran as you know started as a high risk advanced technology proposal. What technology to propose to NASA was a much easier question than “When” will a new technology market for Patran appear and become profitable?

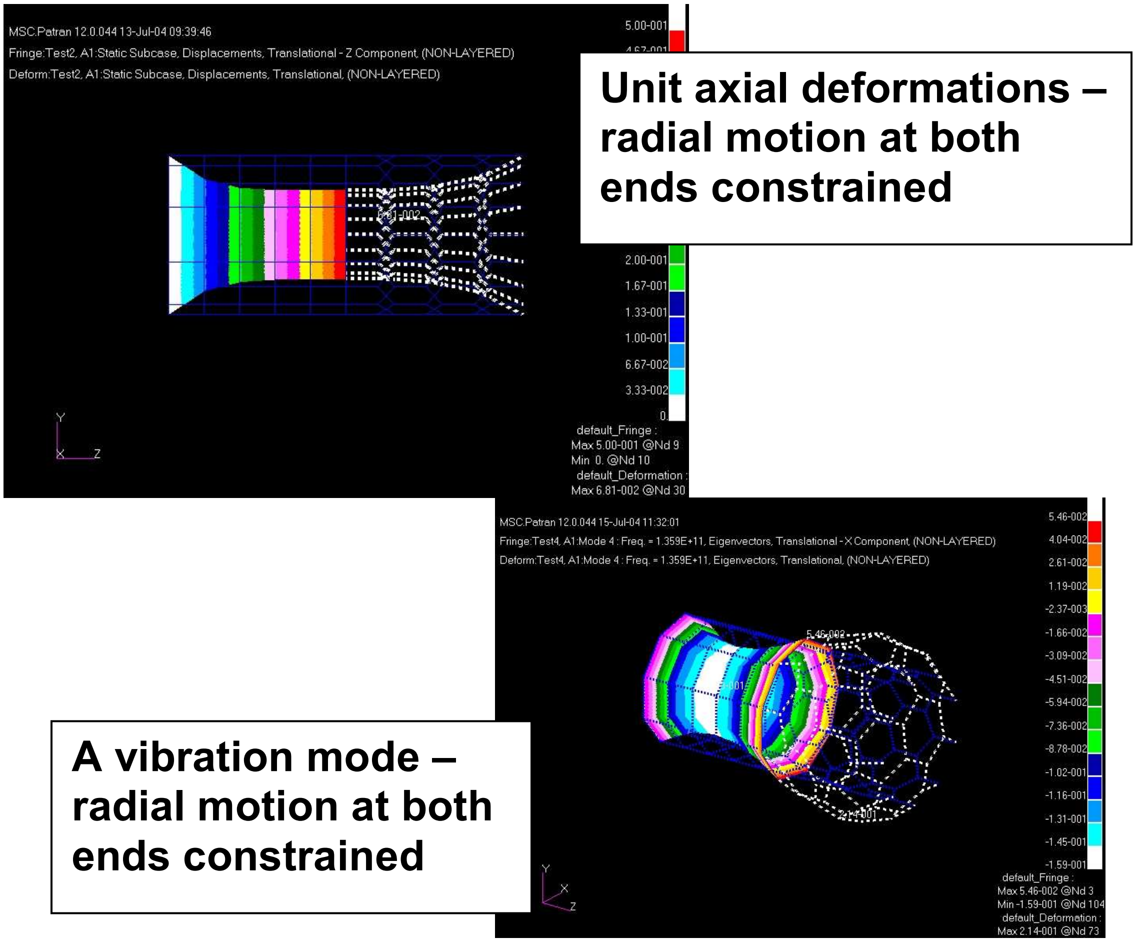
Rapid prototyping is one way of reducing the risk of new technology failures in the marketplace. At PDA we used this approach to design, build and test prototype composite structures at very high temperatures for NASA, the military and for large aerospace companies. That approach worked well for software too and there are ASTM standards for rapid prototype software development. In later years at MSC that approach was not as successful for virtual product development (VPD) software, partly because of our size and later because of SEC concerns that we might have become a monopoly.

Nanotechnology FEM Applications

The modeling of fullerenes and nanotubes using Patran FEM models and Nastran elastic response FEA analyses were first demonstrated in the 2003 NAFEMS paper mentioned earlier. Later a 2005 NAFEMS paper demonstrated that hybrid continuum-molecular models could bridge the gap in scales and simulate elastic deformations and vibration modes for the same nanotube application. In that paper Avagadro's number from NIST tests was used to define carbon point mass elements and serve as a bridge between atomic and continuum mass models. The details are in the paper. Other than attention to detail with unfamiliar nanoscale units the hybrid FEM model was not difficult to build or analyze. The elastic properties were computed using stochastic methods. This empirical approach used published nanotube test results for calibration and required equal work in each half of the hybrid model as a calibration constraint.

The hybrid Patran model produced symmetric static deformation results and nanotube vibration modes. It

was an interesting set of graphics. They showed that in addition to simulation, hybrid models could be useful for imaging molecular vibrations data with color fringes. The images were certainly eye catching.



MSC.Patran 12.0.044 13-Jul-04 09:39:46
Fringe:Test2, A1:Static Subcase, Displacements, Translational - Z Component, (NON-LAYERED)
Deform:Test2, A1:Static Subcase, Displacements, Translational, (NON-LAYERED)

default_Fringe :
Max 5.00-001 @Nd 9
Min 0. @Nd 10
default_Deformation :
Max 6.81-002 @Nd 30

Unit axial deformations – radial motion at both ends constrained

MSC.Patran 12.0.044 15-Jul-04 11:32:01
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Deform:Test4, A1:Mode 4 : Freq. = 1.359E+11, Eigenvectors, Translational, (NON-LAYERED)

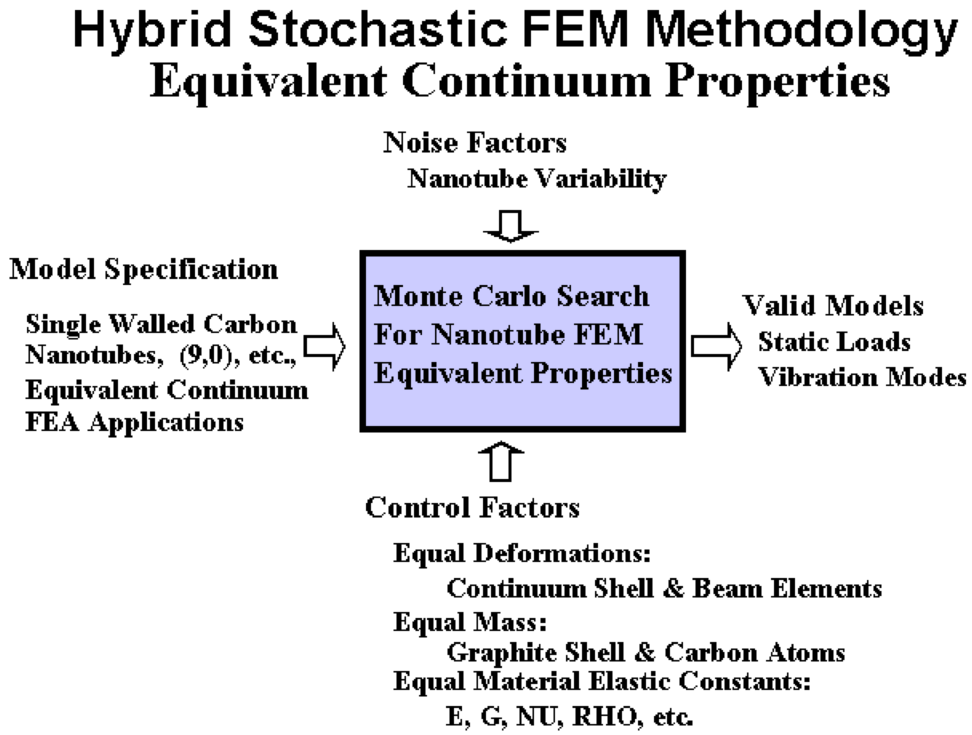
default_Fringe :
Max 5.46-002 @Nd 3
Min -1.59-001 @Nd 104
default_Deformation :
Max 2.14-001 @Nd 73

A vibration mode – radial motion at both ends constrained

Nanotube Hybrid Finite Element Elastic Deformations

The static deformation results were checked against published test results for a (9,0) single walled carbon nanotube before running the vibration mode survey. The schematic below illustrates the process used to generate equivalent continuum properties. It is similar to a Taguchi p diagram for design of experiments.

Noise factors were not used but they could have been used later to include manufacturing processes.



Hybrid Stochastic FEM Methodology
Equivalent Continuum Properties

Noise Factors
Nanotube Variability

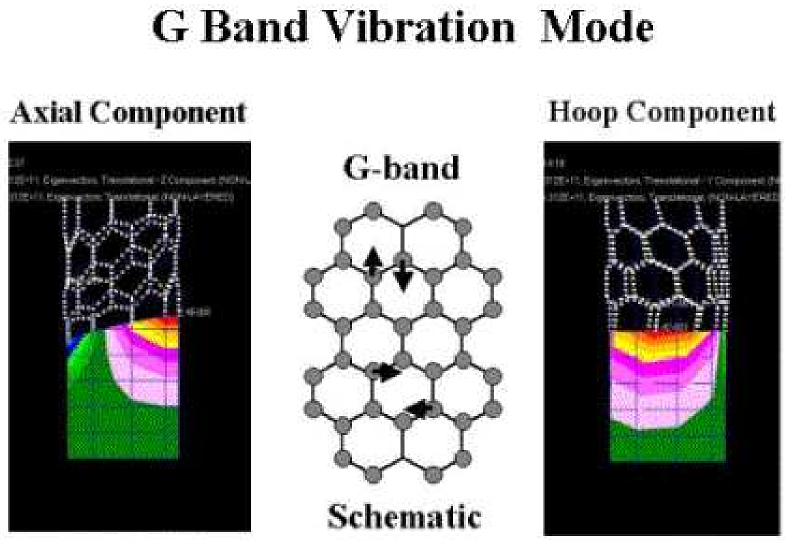
Model Specification
Single Walled Carbon Nanotubes, (9,0), etc., Equivalent Continuum FEA Applications

Monte Carlo Search For Nanotube FEM Equivalent Properties

Valid Models
Static Loads
Vibration Modes

Control Factors
Equal Deformations:
Continuum Shell & Beam Elements
Equal Mass:
Graphite Shell & Carbon Atoms
Equal Material Elastic Constants:
E, G, NU, RHO, etc.

At Raman frequencies, on the order of 10^{13} Hz, a complex G-Band mode shape can be hard to visualize. When you animate the G-Band mode it seems to wiggle wildly in a cylindrical surface with little or no radial motion. It was easier, for me, to see the mode shape by looking at axial and hoop component modes separately. A schematic for G-band data from a 2003 MIT study is compared with the two component mode fringes in the image below. They are in good agreement but the model frequencies were a little lower than the 10^{13} Hz from the Raman spectroscopy test. There is still work to be done in modeling test boundary conditions and constraint calibration details but the hybrid model did work as a bridge between molecular and continuum.



DNA Self-Assembly of Nanostructures

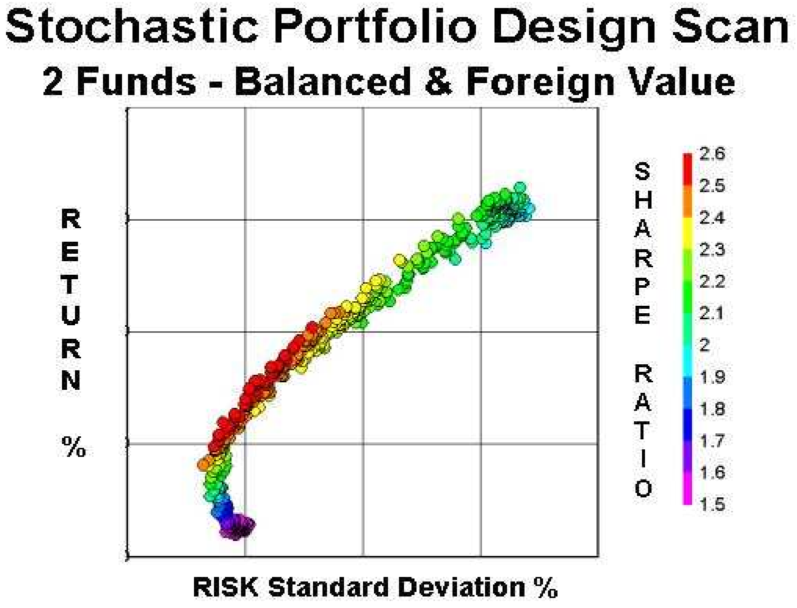
In a very short period after C60 fullerenes and carbon nanotubes were discovered many labs began to try to assemble nanostructures using DNA molecules for assembly. Most were focused on designer molecules for new pharmaceuticals but today some are focused on inorganic nonostructures for new optical and electronic materials. In a few labs researchers have demonstrated DNA-programmable crystallization of face centered cubic and body centered cubic gold nanostructures. Each new issue of Nature and Nature Materials describe yet another use of DNA base pairing to link atoms into a variety of classical shapes including dodecahedrons and other regular polyhedra. Since the base paring taxonomy of DNA codons and Hermite finite element codons are the same, it may be possible to assemble nanostructure material models using the same or similar rules. I am working on it but it will take a lot more than that.

Stochastic Portfolio Design

The chronicles now turn to financial models, a completely different emerging finite element application. The use of finite element technology in finance began several years ago and has been an interest of mine for some time. After PDA went public in 1985 John McDonald, myself, and others evolved our profit sharing plan into a 401k plan. We soon learned that trusting third parties to manage small company retirement funds was risky to say the least. After getting educated by tutors from the school of hard knocks I began to study risk-adjusted returns and value investing on my own. Years later a bout with cancer provided me with the time and a lot more motivation to continue those studies. Out of those later in life studies produced a software tool for portfolio stochastic design scans, PSDS, which has helped me and others design portfolios. The finite element connection is limited and but interesting. It has to do with the representation of actual probability distribution functions as finite domain polynomials rather than infinite domain functions from statistics such as the bell shaped curve of Gauss.

Early math models used by traders like Merton, Black and Scholes were stochastic but scalar and perfectly random. Later Mandelbrot applied fractal geometry models to study market events that are not truly random events and Taleb recently wrote an interesting book about “Black Swan” events. These models are of most interest to traders and have little to do with long term investing no pun intended. My interest was not options trading or any other kind of trading but investing 401k

plan money. Ben Graham and Warren Buffett are my role models although they probably would grimace at the thought of portfolio stochastic design. What the scans do is image the space of all possible portfolios for a specific set of funds in a 401k plan, which might even include Berkshire Hathaway stock if it's in the plan. When only one asset allocation is analyzed using Monte Carlo simulations there is no information provided about all the other portfolios possible with the same funds. That's why I wrote PSDS. It lets the designer see the efficient frontier for the 401k plan funds, which identifies the best risk adjusted return possible in the plan as measured by portfolio Sharpe ratio.

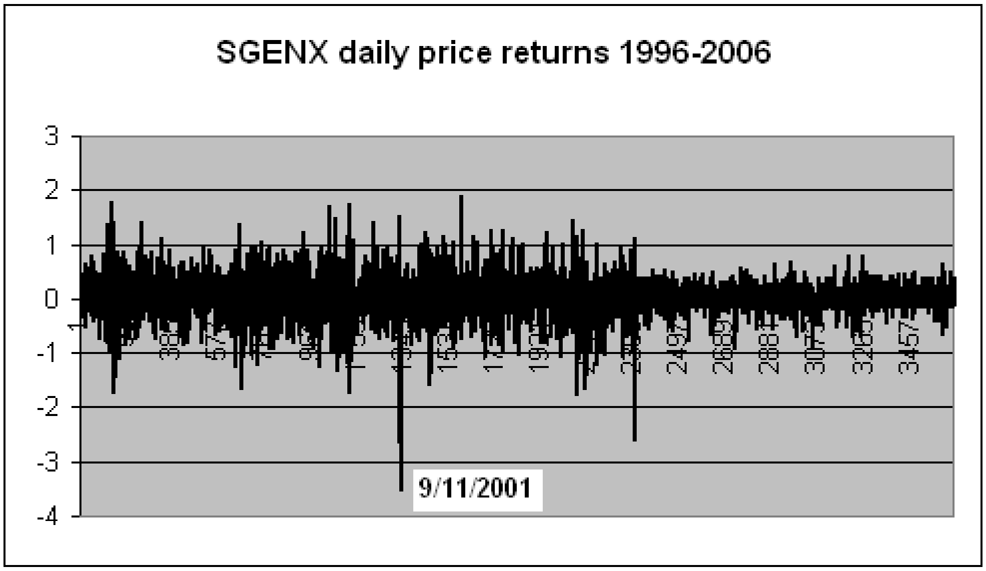


Once again I am getting ahead of myself. The random or bell shaped curved assumed by modern portfolio theory and many engineering models is a good starting point. Financial web sites and newspaper financial pages

compute mean value returns and standard deviations for thousands of funds worldwide. These data can define a normal distribution function or can be used as calibration parameters to construct fund specific probability distribution functions. That's what this section is about.

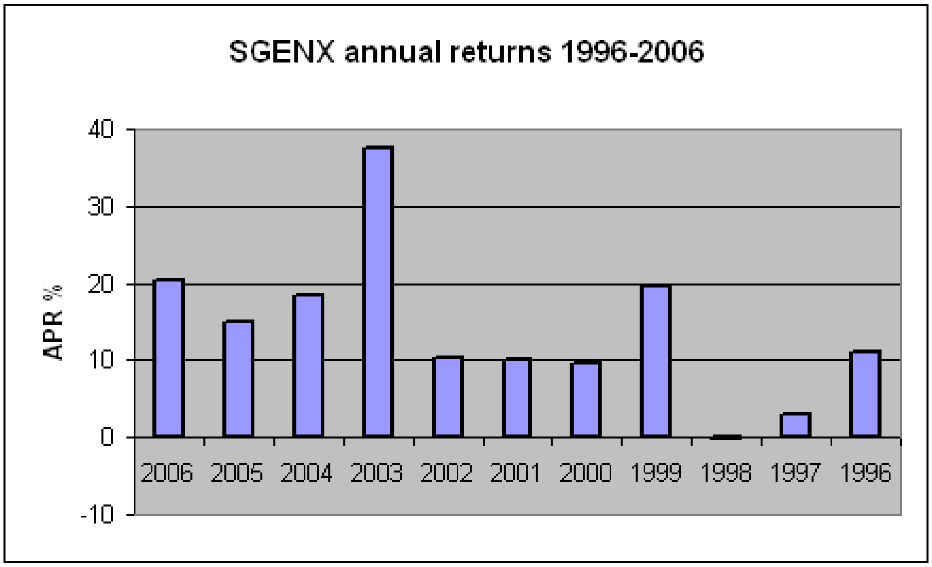
Financial Market Data

When actual fund data are examined on a weekly or daily basis there is noise and occasionally large disruptive changes that for short periods are not modeled well by the bell shaped curve. To illustrate that consider a very stable fund, SGENX, over the ten-year period 1996-2006 which had one very disruptive event.



As noted in books about "Black Swans" after events like 9/11/2001 markets would not have dropped so sharply if markets were truly random. While extreme value events do happen every few years, fortunately things return to normal pretty quickly and the SGENX fund in 2001 had a

positive return of 10%. In fact 1998 not 2001 was the only down year for that fund in this period.

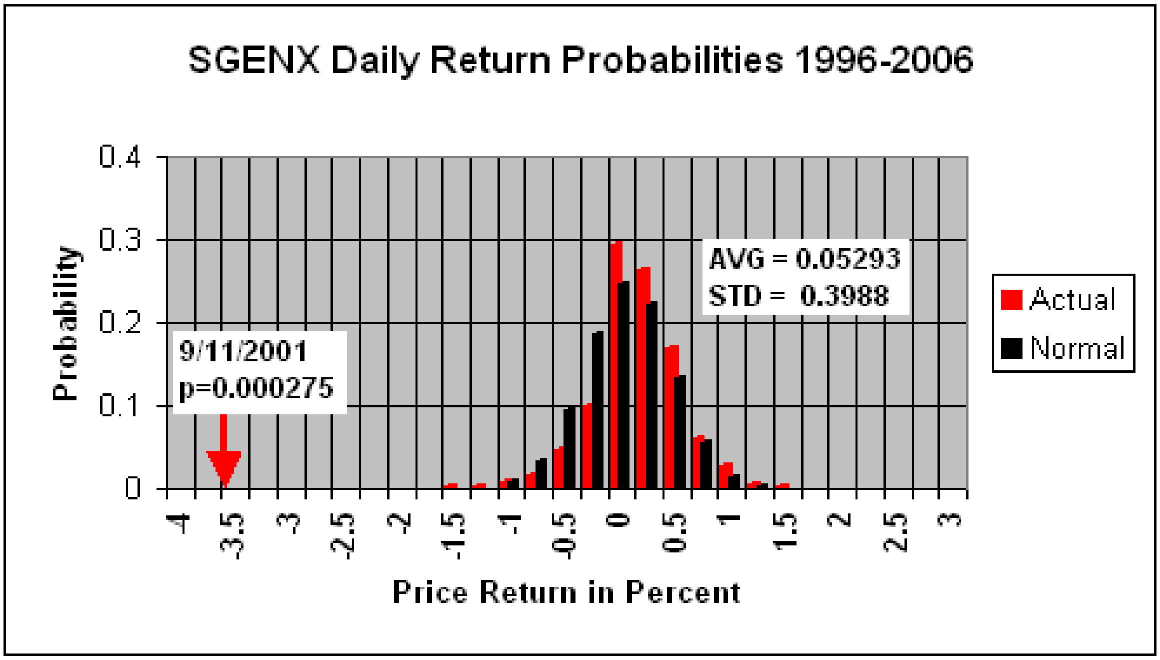


Another "Black Swan" market event happened in 1987 when one day in October the Dow briefly fell 22.6%. Mandelbrot analyzes this event in his book "The (Mis) Behavior of Markets" but even in that year the Dow finished up 4.6%. As Ben Graham once said, "In the end, how your investments behave is much less important than how you behave." Patience is an investor virtue.

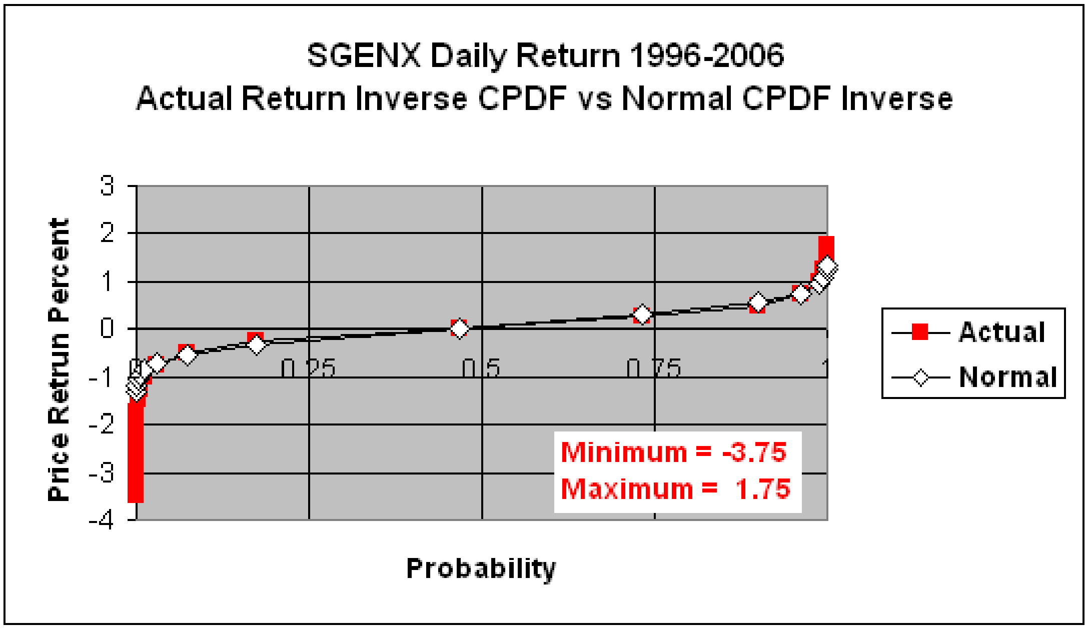
When you think about market data in signal processing terms, high sampling rates usually produce noisy data. If you don't read the WSJ every day, and Warren Buffett does not, the normal distribution function describes the annual data fairly well for most investment purposes. However, as an engineer I would prefer to use an actual distribution function for each fund just as I would always prefer actual test data for material properties in a design simulation. A generic model for a polymer material class may be good for preliminary design but not for actual product design and manufacture. A

material failure in flight puts any vehicle at high risk for structural failure. That's why FAA certification requires a Margin of Safety for each material stress allowable. The financial metaphor might be a Margin of Safety for each fund to keep the portfolio risk to a minimum. The feasibility of doing this depends largely on the question; is it possible to model actual PDFs easily with available market data and cubic Hermite polynomials like those used in computer-aided-engineering design?

First I used a simple frequency response algorithm to construct probability histograms of the actual data for daily, monthly and annual periods. There are many data sources and Yahoo price data is easy to download into a spreadsheet. The image below compares the actual probabilities to the NORMDIST function in Excel for the SGENX average and standard distribution data shown. The extreme event produced 1 data point at –3.5% and no data are above 2.0% in this chart of daily returns for a 10- year period. This was easily done.



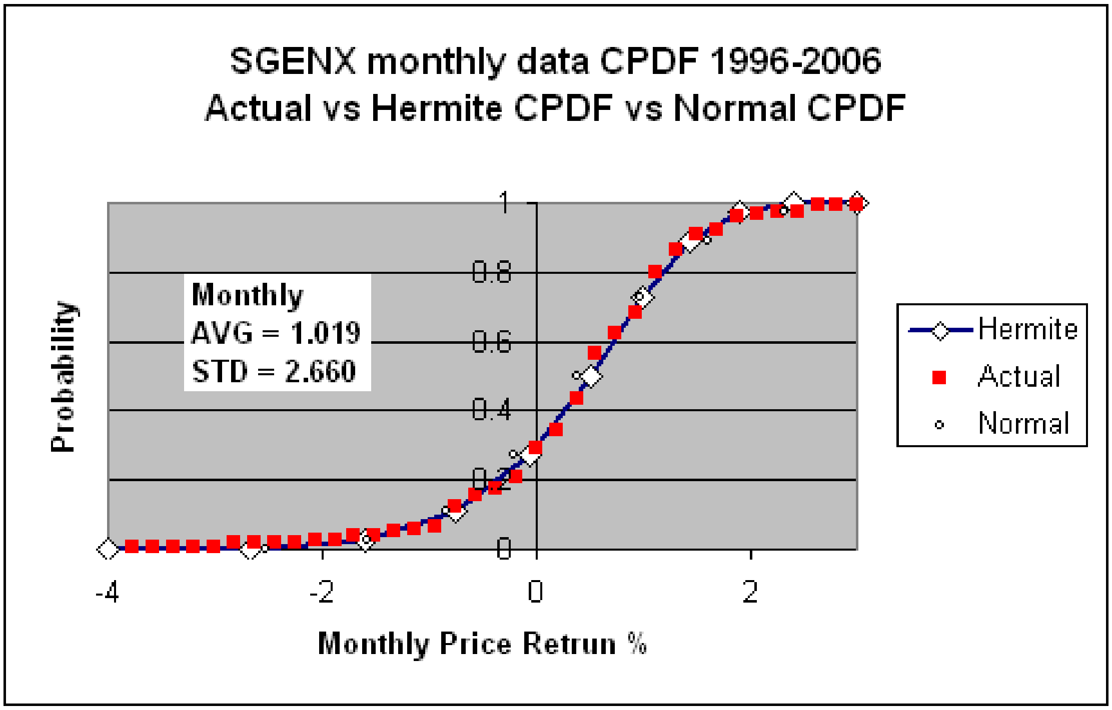
The point of the chart is that the actual PDF is finite. There are no infinities in actual probability data and none are in the actual PDF or its inverse. Nature and markets are finite and the math models I prefer are finite models. Even so the Gaussian PDF and actual probabilities for the daily return data are pretty close for this well designed and maintained fund. To continue to illustrate the point about finite limits and asymmetry I computed and compared the inverse cumulative distribution functions, inverse CPDFs, for the daily data. You need these to do Monte Carlo simulations for stochastic design and this too was easily done.



In general the Normal distribution for a stochastic design scan works fine and I that's what I use today. However, to "stress test" a portfolio I use so-called "fat tail" PDFs like the Cauchy distribution function. In the next section a parametric cubic Hermite polynomial is used to model the monthly CPDF and the question of Hermite feasibility for actual stress testing is addressed.

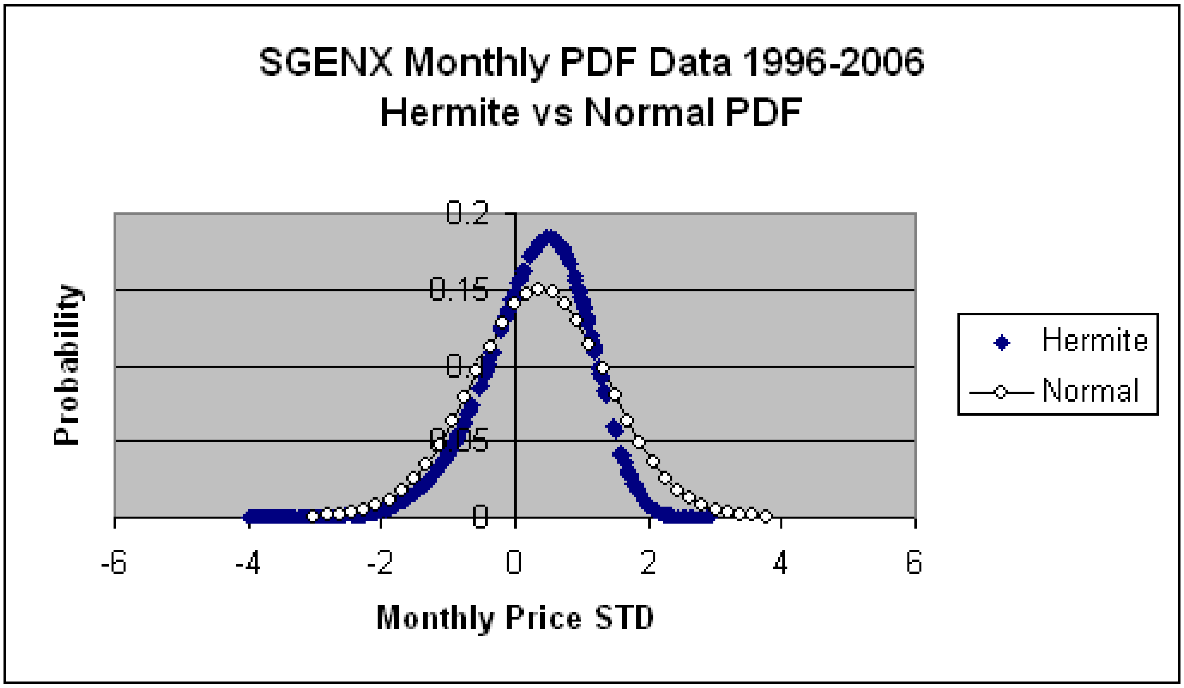
Hermite Distribution Model

Hermite models are powerful and used in the sciences, in engineering and even in the entertainment industry. Continuing with the SGENX fund and data for the 1996-2006 period, I ran several tests of a parametric cubic Hermite model for the actual data for daily and monthly periods. Using the nomenclature introduced earlier, a single polynomial, $H_1{}^S(\xi)$, was used for the CPDF of the actual SGENX data in each period. I can get carried away with the math at times and I apologize but this may be one of those times. The model used nonlinear parameterization of the unit interval and four data points to define the polynomial coefficients. Two of them are the Max and Min return over the ten-year period for SGENX, finite extreme values. The other two are directly related to the APR and STD data used in a normal distribution model. Here monthly SGENX data comparisons were made using standard deviations for



the X-axis for convenience. The results were excellent for the CPDF Hermite polynomial model and for the Normal CPDF. Note that the ratio of period average return to standard deviation for the daily and monthly data increased from 0.0125 to 0.3830 with increasing time periods. That is a factor of 30 improvement. Longer periods filter out noise and very long periods regress to historic means. That is true for experimental data in general. Also, note that the Hermite model is finite with limits specific to the fund data. A Cauchy "fat-tail" stress model would run on to infinity, which is unreal.

A comparison of Hermite and Normal PDF functions for monthly return data show the asymmetry of the Hermite model a bit more clearly. Note that since the Hermite PDF model is based on actual data and not derived from an analytic model it was not used for the inverse CPDF model, a reminder that this Hermite model is empirical.

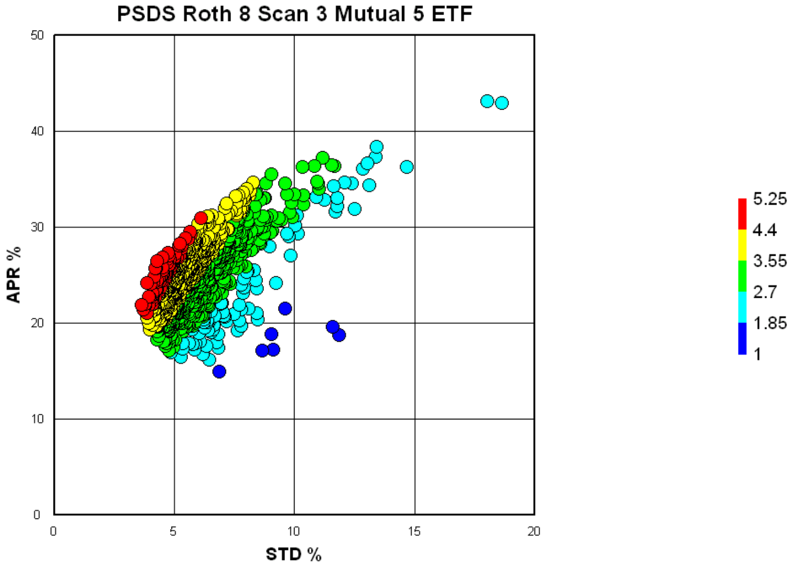


Efficient Frontier Sharpe Ratio Models

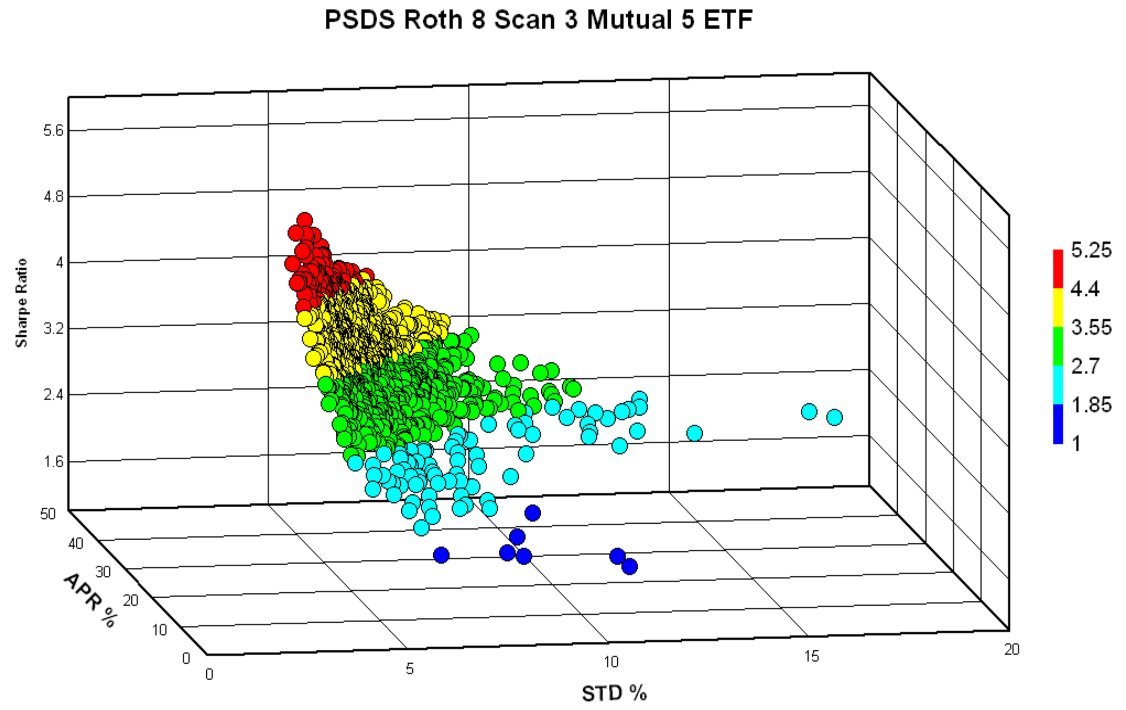
In the first version of PSDS the portfolio design process was basically a two dimensional risk-reward scan of hundreds of possible portfolios. The efficient frontier was a "fuzzy" curve. In the PSDS design scan image for a simple two-fund portfolio shown earlier, color was used to add information about the Sharpe ratio for each portfolio in the scan. When seeking the highest Sharpe ratio for portfolios with ten or more funds I found it helpful to add Sharpe ratio as a third dimension to image the design space.

When you first see a 3D scatter plot of a portfolio design scan you notice that all the points form a surface in space. It's a bit like the inhabitants of Flatland seeing a sphere for the first time. The "cloud of points" are all on a surface in these three dimensions. After seeing this, the mathematics in hindsight tells you that the equation for Sharpe ratio maps the 3D points onto a manifold.

Two-dimensional view of a portfolio design scan.



Three-dimensional view of a portfolio design scan.



Innovation-in-Context

The innovation here is using stochastic design methods from computer-aided-engineering in a financial context. Also, imaging design scan results in three-dimensions, which for me adds additional insight beyond two-dimensional efficient frontier charts. The choice of Sharpe ratio for the third dimension can be changed to Treynor ratio or any similar risk metric that a designer might choose. The use of Hermite distribution models for actual portfolio stress testing is in the nature of a research topic. It uses finite element methods to model margins of safety for actual fund data with finite limits and asymmetry. Hermite models are empirical models and that is useful for portfolio stress testing.

Business Context

A key benefit of portfolio stochastic design scans is the ability to compare a “401k” asset allocation against the best risk adjusted return possible in a company plan. That could be of value to firms who provide investment advice to people who are about to roll over a 401k and begin retirement. There is at least one firm doing that today. The business context is a software tool for portfolio design scans that images several hundred portfolios, risks and returns, and finds the highest Sharpe ratio design.

Epilog

Prof. Lucien Schmit’s engineering graduate students at CWRU, which included myself, first used cubic Hermite polynomials to model elastic shells with conforming finite elements in the 1960s. Prof. Richard Varga and his graduate students at CWRU at the same time proved that piecewise Hermite geometry models are accurate to any desired accuracy and verified that the theoretical convergence rates actually happened in finite precision computer simulations. One of those graduate students, Bob Herbold, went on to become the COO of Microsoft. Professors Schmit and Varga were early leaders in computer modeling using Hermite polynomial models. They were on my Thesis committee and their generous gift of time and talent led me to the Hyperpatch and to the later development of NASA Patran at PDA.

So what comes next in this brave new flat world that Thomas Friedman described so compellingly in his 2005 book even now summarized by Wikipedia on the web. I don’t know but I do have an opinion about the computer aided engineering world that I worked in for years. Global companies and the industries written about in the Chronicles are not going away but they are evolving. Wikinomics driven by peer production, open source innovation and collaboration may or may not be the future of business but the immediate future must focus on alternative energy sources and that will require engineering innovations. We need everything from new materials and processes for batteries and capacitors with very high energy densities at room temperature, to turbocharged stationary fuel cells, to innovative new synthetic fuel processes and the basic competency to do these things with finite resources. There is work to be done.

Acknowledgements

The people who contributed to the success of PDA Engineering and MSC Software were many and I am grateful to them all. John MacDonald my old boss at PDA, Lou Crain and Neil Harrington my teammates on the NASA Patran project were the true believers who first made it happen. The early cast of characters is listed in the Appendix from the 1984 User Conference. Tom Butler at NASA was the genius behind Nastran and he became an early Patran user. Dick MacNeal and Bob Schwendler founded the company that became MSC Software. They had the insight to commercialize Nastran and extended its application to the global auto industry. On the hardware side it was the VAX computer and VMS operating system that first enabled engineering applications at the department level. The first sale of Patran-G was to the Chemical Systems Division of United Technologies as part of their purchase of a VAX computer. Next came Ford Motor, General Electric and later the first international customer British Aerospace; they were all early adopters of the VAX computer and Patran.

Most of us have benefited from computers and software and we owe a debt to giants of the recent past like Turing, von Neumann, and the Bell Labs team that gave us the transistor that changed all our lives. At NASA, PDA and MSC they enabled computer-aided-engineering software that continues to benefit product design worldwide. Today we read about self-organizing web groups that create new ways to succeed in global businesses and I think to myself wasn't that what we were doing a couple of generations ago. In some ways yes but everything has changed and continues to change dramatically with the Internet.

The Patran-G Crew

The 1984 Users Conference in Newport Beach, CA had this list of Patran teammates at PDA Engineering.

Neil Harrington
Lou Crain
Ed Stanton
Paul Zelenski
Roy Russell
Henry Fong
Hayden Hamilton
Richard Gallagher
Maurice Stratton
Mac Casale
Dave Underwood
Kathy Dockendorf
Harris Hunt

Randy Underwood
Clyde Underwood
Doug Campbell
Don Garrett
Daron Libby
Diane Kramer
Brad Call
Julie Arredondo
Floyd Soule
Tony Glinskas
Dennis Sigel
Yvonne Ybarra
Cynthia Underwood
Ray Davis

Several teammates that came along soon after the 1984 Users Conference are listed next in no particular order.

Mike Neilsen
Andy Astor
Klaus Schlemper
Brian Butcher
Stuart Macmillan
John Klintworth
Frank Muller
Ray Amador
Rick Casseli
Ed Peterson

(I may have missed a few, please feel free to post their names in a comment on psdscanner.blogspot.com)

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APPENDIX

Hermite cubic format transformation coefficients

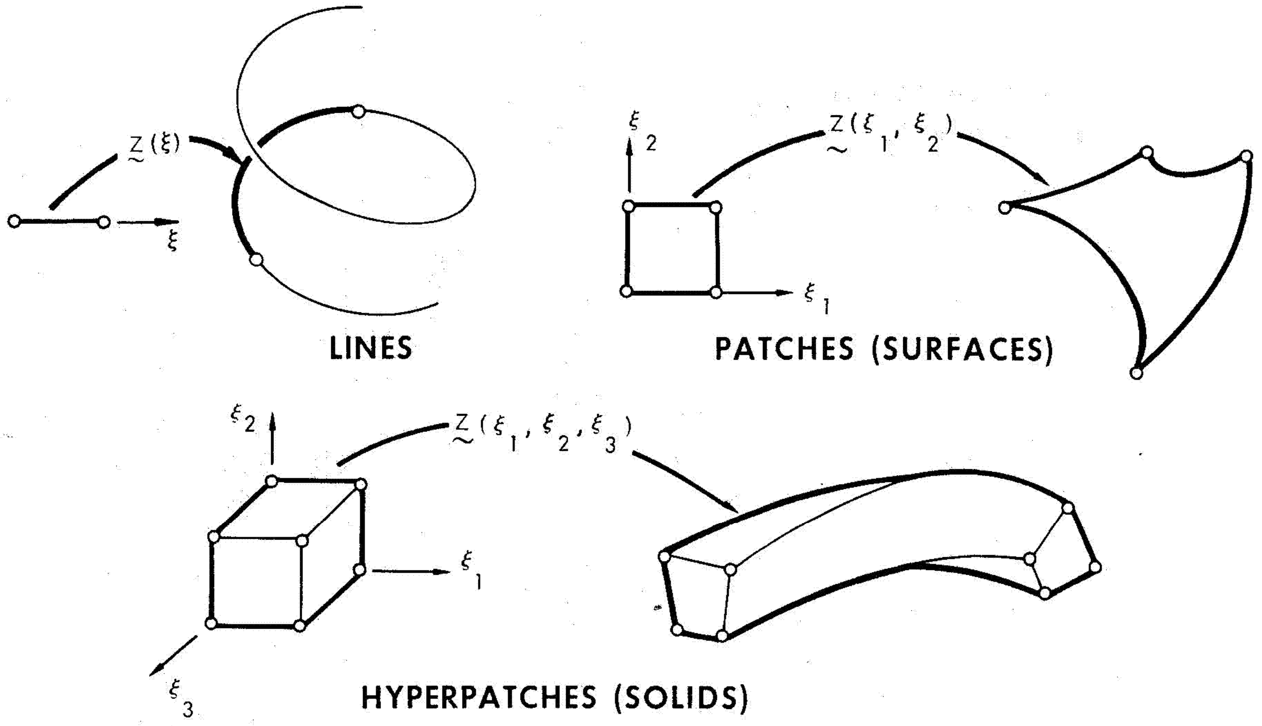
$$[N] = \begin{bmatrix} -9/2 & 27/2 & -27/2 & 9/2 \\ 9 & -45/2 & 18 & -9/2 \\ -11/2 & 9 & -9/2 & 1 \\ 1 & 0 & 0 & 0 \end{bmatrix}$$

$$[M] = \begin{bmatrix} 2 & -2 & 1 & 1 \\ -3 & 3 & -2 & -1 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}$$

GLOSSARY

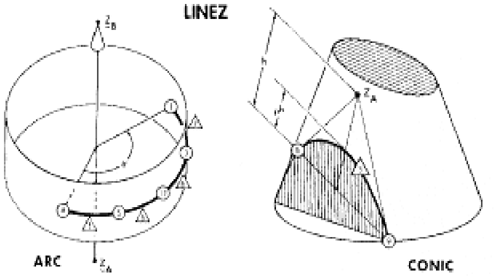
FEA – Finite Element Analysis
FEM – Finite Element Model
MEMS - MicroElectroMechanicalSystem
NEMS – NanoEletroMechanicalSystem
ISO – International Standards Organization
W3C – World Wide Web Consortium
CML – Chemical Markup Language
XML – Extensible Markup Language
VMS – Virtual Memory System
DEC – Digital Equipment Corporation
SIGGRAPH – ACM Special Interest Group for Graphics
ALC – Air Force Logistics Command
JANNAF – Joint-Army-Navy-NASA-Air Force Interagency Propulsion Committee

PATRAN-G Hermite Geometry

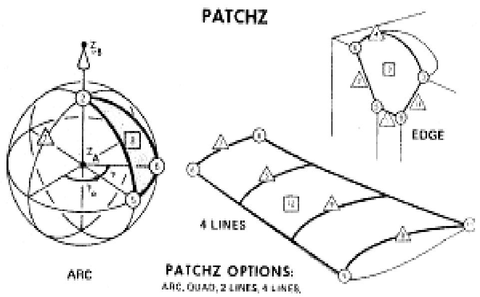


PARAMETRIC CUBIC GEOMETRY

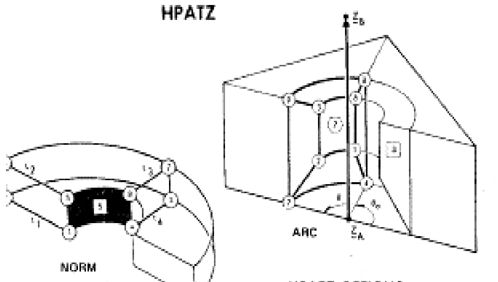
Patran-G Initial Geometry Options



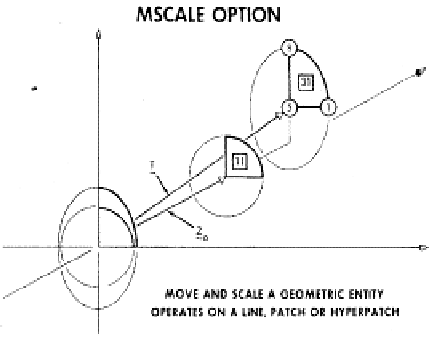
LINEZ OPTIONS:
ARC, CONIC, STR, SPLINE, BLEND, PWL,
POINT, GEOMETRIC, ALGEBRIC, GAUSSIAN, DELETE



PATCHZ OPTIONS:
ARC, QUAD, 2 LINES, 4 LINES,
GLIDE, EDGE, NORM, BLEND,
MSCALE, POINT, GEOMETRIC,
ALGEBRAIC, GAUSSIAN, DELETE



HPATZ OPTIONS:
HEX, NORM, ARC, 2 PAT, 4 PAT, BLEND,
MSCALE, POINT, GEOMETRIC, ALGEBRAIC,



MOVE AND SCALE A GEOMETRIC ENTITY
OPERATES ON A LINE, PATCH OR HYPERPATCH