

United States Department of Energy
Integrated Manufacturing & Processing Predoctoral Fellowships

FINAL REPORT

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Program Overview

Recognizing the increasing loss of competitiveness of the United States in manufacturing, the U.S. Department of Energy (DOE), Office of Basic Energy Sciences-Engineering Research Program, initiated in July 1992 a predoctoral fellowship program in integrated manufacturing and processing. The program, which awarded twelve fellowships annually, was administered by the Fellowship Office, Policy and Global Affairs Division of the National Research Council with guidance from the National Academy of Engineering.

The objective of the program was threefold: to create a pool of PhDs trained in the integrated approach to manufacturing and processing, to promote academic interest in the field, and to attract talented professionals to this challenging area of engineering. It was anticipated that the program would result in the creation of new manufacturing methods that would contribute to improved energy efficiency, to better utilization of scarce resources, and to less degradation of the environment. Emphasis in the competition was on integrated systems of manufacturing and the integration of product design with manufacturing processes. Research addressed such related areas as aspects of unit operations, tooling and equipment, intelligent sensors, and manufacturing systems as they related to product design.

Each year fellows submitted end-of-the year reports outlining progress on their research proposals, courses taken, papers written, and professional meetings attended. When they completed fellowship tenure, they were invited to attend a symposium of fellows held in Washington, DC where they could present their research. Copies of their abstracts are attached.

Due to budget reductions, the Engineering Research program was discontinued in 1999. No new fellowships were awarded after the 1999 competition. The remaining funds in each of the U.S. Department of Energy grants were used to pay the stipends (\$20,000 per year) and cost of education allowances (up to \$15,000 per year per fellow) for fellows still supported by the program. Funds were also used for an annual symposium of Integrated Manufacturing and Processing Predoctoral Fellows held in Washington, D.C. The last symposium was held in the fall of 2002 after the 1999 fellows completed their tenure.

The National Academy of Engineering

Founded in 1964, the National Academy of Engineering (NAE) provides engineering leadership in service to the nation. It operates under the same congressional act of incorporation that established the National Academy of Sciences, signed in 1863 by President Lincoln. Under this charter, the NAE is directed "whenever called upon by any department or agency of the government, to investigate, examine, experiment, and report upon any subject of science or art." The NAE is a private, independent, nonprofit institution. In addition to its role as adviser to the federal government, the NAE also conducts independent studies to examine important topics in engineering and technology. It has more than 2,000 peer-elected members and foreign associates, senior professionals in business, academia, and government who are among the world's most accomplished engineers. They provide the leadership and expertise for numerous projects focused on the relationships between engineering, technology, and the quality of life.

**United States Department of Energy
Integrated Manufacturing & Processing Predoctoral Fellowships**

Fellows Supported Under Award No. DE-FG02-93ER14371

94 Cohort

Dr. Richard Dessenberger
Dr. Joseph Donoghue
Dr. John Hogan
Dr. Evan Kempner
Dr. Mark Lawley
Dr. Craig Lawrence
Dr. Mark Martin
Dr. Andrew McAfee
Dr. Michael Nechyba
Dr. James Neely
Dr. Cynthia Regan
Dr. Crid Yu

Research Institution

U. of Illinois at Urbana-Champaign
University of California, San Diego
Georgia Institute of Technology
University of California, Los Angeles
University of Illinois at Urbana-Champaign
Stanford University
Stanford University
Harvard University
Carnegie Mellon University
Massachusetts Institute of Technology
Virginia Polytechnic Institute & State U.
University of California, Berkeley

97 Cohort

Dr. R. Reid Bailey
Dr. Jonathan Briggs
Dr. Ryan Durante
Dr. John Kietzman
Dr. Steven Kmenta
Dr. Debra Krulewich
Ms. Elaine Linde
Dr. Robert Monahan
Dr. Eva Regnier
Dr. Stephen Rock
Dr. Michael Schabel
Dr. Aimee Smith

Research Institution

Georgia Institute of Technology
University of Pennsylvania
Rensselaer Polytechnic Institute
Stanford University
Stanford University
University of California, Berkeley
Purdue University
Purdue University
Georgia Institute of Technology
Rensselaer Polytechnic Institute
University of Arizona
Massachusetts Institute of Technology

99 Cohort

Dr. Matthew Joseph Bono
Dr. Anh Xuan-Hung Dang
Dr. Ty Grant Dawson
Mr. Vincent DiFilippo
Ms. Krista Marie Donaldson
Dr. Chad Edward Duty
Dr. Russell Keith Edwards
Dr. Dathan Shane Erdahl
Dr. Carol J. Romanowski
Dr. Shadrach Joseph Roundy
Dr. Andrew Joseph Scholand
Dr. Brooke Suzanne Stutzman

Research Institution

University of Michigan - Ann Arbor
Georgia Institute of Technology
Georgia Institute of Technology
Tufts University
Stanford University
Georgia Institute of Technology
University of Utah
Georgia Institute of Technology
State University of New York at Buffalo
University of California, Berkeley
Georgia Institute of Technology
University of Michigan - Ann Arbor

Resin Transfer Molding Process

Dr. Richard B. Dessenberger, Doctor of Philosophy in Mechanical Engineering

Resin transfer molding (RTM) is a process for producing fiber-reinforced polymer matrix composites. A preform of dry reinforcing fibers is placed inside a closed mold, and a liquid resin is injected into the mold to fill the spaces between the fibers. The resin then cures, forming a stiff, solid composite that can be removed from the mold.

In the manufacture of fiber-reinforced composite parts by RTM, the fabrication of the fiber preform is critical to both part quality and production efficiency. During the fiber preforming process, a sheet of fibers is deformed by stretching and pressing to conform to the surface of the mold. The deformation induced by preforming introduces porosity and permeability variations which affect mold filling, and may result in defects (tears and wrinkles) in the preform. Many aspects of production efficiency and part quality are also determined during the injection and curing phases of RTM. These include filling time, final degree of cure, void content and residual stresses. The process can be very complex, and a fundamental understanding of the physics is essential to ensure quality part production. This work addresses two topics: fiber preforming and non-isothermal mold filling.

In this study, a mathematical model for analyzing fiber preforming of thermoformable random fiber mats is developed. Fiber preforming is modeled using a type of ideal forming theory which maps an initial sheet of fibers to the mold surface. The mapping is established by minimizing the value of a "formability function" integrated over the mold surface. The formability function is a measure of the local deformation, and exhibits large values under conditions that promote either tearing or wrinkling of the mat. Uniaxial elongation, pure shear and biaxial stretching experiments are performed to evaluate the formability of the random fiber mat used in the investigation. The mathematical model is incorporated into a numerical simulation for arbitrarily shaped three-dimensional preforms. Results of the simulation include the shape of the initial fiber sheet and values of both the formability function and the principal stretch ratios over the mold surface. This information is used to predict the presence of defects in the preform. Example calculations are shown for several preforms.

In this investigation, a set of volume averaged balance equations to model non-isothermal mold filling in RTM is developed. The model is incorporated into a numerical simulation of mold filling. The energy equation is based on porous media theory and includes a dispersion term. The dispersion term represents an enhanced transport of heat due to local fluctuations in the fluid velocity and temperature away from their average values. Non-isothermal molding experiments are performed to investigate and quantify dispersion effects relative to RTM processes. Good agreement is found between the experimentally measured and numerically predicted temperatures. The results indicate that thermal dispersion is important in RTM processes and *must* be included in simulations to obtain accurate predictions.

These mathematical models for preform manufacture and mold filling should help engineers to design parts and tooling, optimize operating conditions, and shorten the time required to produce low-cost, high-quality net-shape RTM parts.

A Study of Product Stability During Production Ramp-Up

Dr. Joseph P. Donoghue, Doctor of Philosophy in Mechanical Engineering

This research addresses a concept in product development and manufacturing referred to as product stability. During production ramp-up when the state of knowledge about the product is extremely low, the organization can be hit with design or process problems. After some time in production, the organization learns more about the product design and the manufacturing processes. This learning results in a better understanding of key variables affecting product performance and manufacturing processes, which, in turn, creates a predictable production environment.

A working definition of product stability was developed for the purpose of establishing variables to evaluate during product ramp-up. *Design stability* refers to the robustness of the product performance, and *product stability* refers to the ability to manufacture the product at required volumes and cost goals. To evaluate the manufacturing processes, the piece-part fabrication processes (Piece-Part Fabrication Capability), assembly processes (Cycle Time Efficiency and Adjustment/Calibration Capability), and factory learning variables (Internal Product Failure Rate and Factory Utilization) must be monitored. The product design variables include direct labor hours and costs of materials to meet production volumes, and staffing required to execute the production and quality plan.

Many of these variables were evaluated using Hewlett-Packard CopyJet and PhotoSmart printer production data. A model for finished-goods inventory was developed and used to predict the PhotoSmart inventory. This prediction was compared to the actual PhotoSmart performance and original organizational predictions. The monthly prediction error of the model and organization error for the three months prior to PhotoSmart introduction were 0.52% and 10.10%, respectively.

Minimum Aisle Width Path Planning for Nonholonomic Mobile Robots in Industrial Environments

Dr. John E. Hogan, Doctor of Philosophy in Mechanical Engineering

Industrial facilities that use mobile robots, such as automated guided vehicles (AGVs), must be particularly concerned with the path planning of these vehicles due to the high cost of floor space and ever-present safety concerns. A path that minimizes the required aisle widths for maneuvers can lower costs by increasing floor space utilization and improving safety.

The vehicles investigated in this research have nonholonomic kinematic constraints due to rolling wheels which restrict vehicle motion and make path planning and analytical solutions more difficult. Lower bound solutions are obtained. Solutions to simple and complex nonholonomic paths are determined for vehicles and environments commonly found in industrial facilities.

In determining the minimum aisle width path solution, the equations of motion and path equations for any point on the vehicle are formulated in terms of general vehicle parameters. A cost function comprised of the weighted sum of aisle widths is formulated and minimized. Rather than a blind search for the absolute minimum, conditions based on the parameters of the vehicle and environment are developed to determine the absolute minimum of the cost function and the minimum aisle widths. The critical path is defined as the portion of the entire path that completely defines the aisle widths and is the only portion of the path that must be followed in order to result in minimum aisle widths. The minimum aisle width solution in terms of general vehicle parameters is then mapped to specific steering mechanisms to determine vehicle inputs. From the solutions presented, a general solution procedure is defined to solve the problems presented and is used to extend this research to other problems of interest.

Analytical equations are given throughout the majority of the research enabling analytical proofs to be developed and providing additional benefits in practical applications. Simulation experiments, using the equations developed, are performed to test and validate the research. Examples of applications of the research are presented for vehicle path design and facility layout. In addition, the research can be used to determine vehicle specifications and capabilities and is applicable to areas outside industrial environments.

Embedded Fiber Optic Strain Sensors for Process Monitoring of Composites

Dr. Craig M. Lawrence, Doctor of Philosophy in Mechanical Engineering

Fiber-reinforced polymer-matrix composite materials are used in many aerospace and industrial applications. To produce these materials, strong, stiff reinforcing fibers are surrounded by a lightweight polymer matrix to create a material which takes advantage of the beneficial mechanical and thermal properties of both constituents. The increased use of composites in structural applications has led to concern about the reliability of these materials. In particular, residual stress introduced during processing is cited as one of the most significant problems in the fabrication of composite structures. These stresses can lead to warping, cracking and reduced strength of composite parts.

In this presentation, a new method to measure residual stress during the processing of polymer-matrix composites - the embedded fiber optic sensor (EFOS) method - is described. In this method, residual stresses are computed from embedded fiber optic strain sensor measurements using a viscoelastic, cure-dependent numerical process model. The EFOS method has the advantage that it is non-destructive and provides information on residual stress development during processing in real-time. Experiments to validate the method for graphite/epoxy composites will be described. If time permits, additional work on the development of a novel multi-parameter fiber optic sensor for embedded applications will be presented.

Design for Variety: A Methodology for Understanding the Costs of Product Proliferation

Dr. Mark V. Martin, Doctor of Philosophy in Operations Management

As companies look for ways to stay competitive in the global marketplace, the concept of mass customization has appeared as a potential advantage. Utilizing new manufacturing and information technologies, companies are trying to determine the amount of variety that they should offer to optimize profits. My research is focused on methods to help project leaders and engineers estimate and manage the costs of providing this product variety. Since the tools being developed are for use during the design or redesign stage of a product, we are referring to the research as Design for Variety (DFV).

I am focusing on three major dimensions in this research: 1) product and process design options and costs, 2) manufacturing costs of providing variety, and 3) customer preference for variety. Design tools and techniques such as modular designs and late-point identification can assist engineers in evaluating the design options; mathematical models of production operations can assess the manufacturing cost of providing variety for a given product/process design; and engineers can use methods such as Quality Function Deployment (QFD) and conjoint analysis to elicit customer preferences regarding variety.

My work looks at utilizing these concepts and new ones to give a comprehensive picture of the cost and quality issues associated with the mass customization of products. By calibrating and applying these concepts to specific business cases, we will prove the feasibility of the methodologies. We have established contacts at HP, Boeing, Denso International, and Ford, and are developing links with others to apply the methods.

If successful, the research will demonstrate the validity of integrating these concepts and will serve as a new approach for linking variety, product design, and manufacturing process design. Companies utilizing the methods will establish wider customer bases while reducing life-cycle costs, shortening the production cycle, and accelerating their market response.

Learning and Transfer of Human Control Strategies

Dr. Michael C. Nechyba, Doctor of Philosophy in Robotics

Over the past three years, we have developed several new methodologies critical for the modeling and transfer of human control strategy (HCS) in response to real-time inputs. The problem has significant impact in a variety of applications, such as agile manufacturing, the Intelligent Vehicle Highway System (IVHS), human-machine interfacing, and real-time training. The research provides a framework for abstracting human skills so as to facilitate analysis of human control, to develop human-like intelligent machines, to allow robots to learn from human partners in human-robot coordination, and to transfer skill from human to human through learning human-machine interfaces. In the thesis, we are addressing the following issues: (1) how to efficiently model human control strategy, (2) how to select state inputs in order to generate reliable models, (3) how to validate the computed models, (4) how to evaluate the quality of the HCS models, (5) how to optimize performance of the HCS models, and (6) how to effectively transfer human control strategy.

We have developed two novel modeling approaches for abstracting human control strategies. The first has been extensively developed and combines efficient cascade neural networks, where hidden units with variable activation functions are added one at a time during training, with node-decoupled extended Kalman filtering, adapted from the theory of optimal filtering. We have shown that the two concepts complement each other well by compensating for the other's weaknesses. Together, the resulting learning architecture converges orders of magnitude faster to better local minima than other neural network architectures and training algorithms. Our second approach has been developed more recently and utilizes Hidden Markov Models (HMMs) to stochastically map input-space sequences to output probabilities for given actions. Because this control scheme is stochastic and discontinuous, it can better represent certain human control strategies involving switching between several discrete action choices.

We have also developed a Hidden Markov Model-based similarity measure, capable of comparing and contrasting dynamic, stochastic, multi-dimensional human control trajectories. We have proven well-behaved properties of the measure, and have tested it by comparing control trajectories for different individuals. While our similarity measure succeeds in correctly classifying all the control strategies belonging to the same individual, more conventional statistical techniques, like the Bayes optimal classifier, fail for the same task. We are currently using this similarity measure to validate learned HCS model performance by comparing the human control strategy with the model-generated control strategy in the feedback loop. By connecting the similarity-based validation procedure to the learning through some stochastic optimization algorithm such as genetic optimization or simultaneously perturbed stochastic approximation, we can refine the model's input representation to arrive at more satisfactory models.

Improving Project Valuation to Support Research and Development Planning

Dr. James E. Neely, III, Doctor of Philosophy in Technology, Management and Policy

Research and development (R&D) is a critical source of competitive advantage in many industries, but efficient investing is crucial because resources for conducting R&D are limited. Considerable pressures to reasonably value R&D result. However, many common analysis frameworks, including net present value and two-dimensional matrices, fail to value R&D adequately. Important aspects of project value, including performance issues and the ability to actively manage efforts, are systematically overlooked or trivialized because they are difficult to quantify. Unfortunately, these features constitute the bulk of R&D value in many cases.

This research focuses on improving R&D valuation by explicitly revealing important, often hidden sources of project value. Recognizing that no single metric is equally applicable to all types of projects, several frameworks are integrated into a methodology that addresses deficiencies in current valuation practice. Decision analysis and real options models are applied directly to value projects which predominantly yield traceable financial benefits. Utility analysis serves as a precursor for valuing projects which provide multiple benefits, many in the form of technical capabilities advancements.

The end result is a better metric of project value. This can be applied on a stand-alone basis to enable more meaningful project comparisons, or combined with other metrics as part of an overall R&D management process. By improving decisions at the R&D stage, this work should enhance a firm's ability to develop efficient manufacturing processes and salable products. Utility is especially promising for this purpose because it integrates end-user preferences into the development and design process.

A practical demonstration of the methodology is being developed through its application to a portfolio of materials technology related projects at a major automotive producer. This presentation will highlight the main elements and advantages of the methodology. General results to be expected from the portfolio assessment will also be discussed.

A Concurrent Engineering Framework for Apparel Manufacturers

Dr. Cynthia L. Regan, Doctor of Philosophy in Clothing and Textiles

The purpose of the present study was to develop a concurrent engineering (CE) apparel framework. Sequential manufacturing is the traditional production method for apparel manufacture. Sequential design and product development impact manufacturing more than any other process because design decisions can have costly production implications. To improve this process, other industries have implemented CE. CE is the concurrent design of products and their related manufacture and support processes. Reported CE benefits are time, cost, and quality improvements. A review of CE literature showed no application of CE for apparel manufacture.

The present study was an interpretational qualitative case study of apparel manufacturers with two phases: Phase One was a descriptive documentation mapping the *as is* environment. Phase Two was a development of a *to be* environment that integrated apparel design with product development. The apparel manufacturer sample was located in the U.S., representing multiple merchandise classifications. Sample size was 72 subjects for Phase One and 36 subjects for Phase Two. A triangulated data collection method combined interviewing, reading company documents, observing, and giving questionnaires to focus groups.

Phase One results and discussion narrative are 101 IDEF0 analytic graphic diagrams and identification of process performance weaknesses for the *as is* environment. IDEF0 diagrams include: create apparel line, develop colors and prints, implement fabric and special operations, set production specifications, and produce samples. Findings documented the *as is* environment as a sequential process with rework cycles occurring in all functional areas. The *as is* environment had time-to-market delays, excess cost, and decreased process quality.

Phase Two results and discussion for the *to be* environment was the development of a CE apparel framework. The findings are illustrated in 80 IDEF0 diagrams with reorganization of apparel activities, inclusion of multi-disciplinary design teams, and use of enabling technology. The *to be* environment findings show apparel activities did not remain sequential. Apparel activity movement supports the CE design maturity curve concept in which apparel design decisions moved later, and manufacturing and costing decisions are made earlier. An apparel associate focus group indicated that the *to be* environment could improve moderately for time-to-market, excess cost, and process quality.

Assessing Society's Nutrients: An Ecological Approach to Modeling Industrial Material Flows

Dr. Robert Reid Bailey, Doctor of Philosophy in Mechanical Engineering

Material flows represent one of the strongest, most inextricable links between natural and industrial systems. With increasing environmental problems, understanding material flows in industrial systems has never been more crucial, yet at the same time never more difficult due to their complexity. To better understand systems of material flows in industry, the validity and usefulness of *input-output flow analysis* are investigated in this research. With direct roots in ecology, flow analysis is composed of a unique, versatile and adaptable array of tools capable of modeling complex industrial systems of material flows and facilitating the synthesis of new systems. The core capabilities of flow analysis include the characterization of system behavior with *metrics* and the tracing of material flows through systems with *environs*.

The flow analysis metrics, including measures of material cycling, are connected to controllable aspects of flow systems and to environmental objectives. By connecting controllable system features to environmental objectives, the metrics enable the synthesis of changes to flow systems. Beyond metrics, flow *environs* allow a modeler to trace material flows through a system. Environs are useful for in depth analysis of the structure of a material flow system. The usefulness of the metrics and environs is evaluated in the context of material flows in industrial systems with four case studies ranging from material flows of an entire nation to flows of a single product from a single company. In this presentation, the application of flow analysis to industrial material flows is introduced and examined in the context of one case – the domestic material flow case – to highlight the capabilities of flow analysis and demonstrate how it is connected to the synthesis of new systems.

Improving the Accuracy of Machine Tools by Correcting for Predictable Machine in Process Errors

Dr. Debra A. Krulewich Born, Doctor of Philosophy in Mechanical Engineering Controls

The goal of my research is to improve the accuracy of machine tools with minimal increase in cost. I will accomplish this by correcting for predictable machine in process errors using the machine controller. Software error compensation is not widely used in industry because (1) current methods of measuring geometry induced machine errors are time intensive and require expensive equipment and highly skilled labor, and (2) there are no robust methods for predicting thermally induced errors, which can account for as much as 70% of the total error. Furthermore, most machine controllers are "closed", and don't allow the user access to perform these corrections. During my research, I have developed an efficient method to measure the geometry-induced errors. I have also developed a robust modeling technique to predict thermally induced errors. I am currently working with Lawrence Livermore National Laboratory to implement this compensation on an "open architecture" controller.

The geometric error model is formulated from the kinematic relationships between each moving axis. The axes errors are expressed as functions of commanded positions and then combined to predict the error between the tool and part. Next, a series of distances between several fixed base locations from the part table and various tool positions in the work volume is measured using a Laser Ball Bar (LBB). The non-linear error model is fit using the measured distances. I have mapped the errors of a three-axis machining center and successfully predicted the total error to better than 85% accuracy.

The model for thermally induced errors is based on the assumption that the temperature distribution in a particular region on a machine can be estimated by a polynomial. Since the thermal error is related to the integral of the temperature profile rather than the entire temperature profile, I use numerical integration techniques to estimate the integral of the temperature profile. Using Gaussian integration techniques, I select the number and location of temperature measurements on the machine structure to monitor. Because the numerical integration model is dependent only on the order of the polynomial, the same model will track under varying boundary conditions, including warm-up and cool-down cycles as well as changing velocities and environmental conditions. I have validated this method through simulation for cases where the closed form solution exists. I am currently evaluating this method both on a test stand and using finite element analysis.

Modeling and Control of Shape Memory Alloy Composites

Dr. Jonathan P. Briggs, Doctor of Philosophy in Mechanical Engineering

The control and modeling of embedded SMA actuators (a composite) has become a recent topic of interest in the field of smart structures. The inherent difficulties associated with SMA actuators has resulted in a divergence between the purely control theoretic and solid mechanics based researchers. Control systems for SMA composites can benefit greatly from a more complete understanding of the mechanics issues involved when such information is extractable over appropriate time scales. Homogenization provides a simplified, yet mathematically rigorous, method of generating average stress and strain fields in a composite, and in recent years has been extended to include nonlinear constitutive behavior as well. Our research has focused on developing homogenization for SMA composites and using the results to deal with the issues of a truly continuous nonlinear system.

Dr. Ryan J. Durante, Doctor of Philosophy in Mechanical Engineering

As product lifecycles become shorter, there exists a growing tendency in industry to place more emphasis on agile manufacturing systems – systems with a need for flexibility at a scale not previously achievable. Recent years have revealed a shift in paradigms from attempting to exploit economies of scale to economies of scope. The ability to quickly adapt to changing market forces, product designs, and changing technologies is now a key requirement to the survival of an organization. Agile automation is the response to that need. For years now, industry has led academia in the industrial automation field. Heuristic processes for designing conventional hard automation have been created through trial and error. A formal design methodology for creating such systems is still lacking even today. The problem is exacerbated when these conventional methods are applied to agile systems which are vastly more complex. As a result, agile systems, as well as all but the simplest conventional automation systems are prone to run over- budget, produce both over and under designed components, are difficult to debug, provide for little component reuse, and are extremely difficult to maintain and upgrade.

A new design process is needed. This thesis introduces a user-orientated UML-based design methodology for integrating large-scale agile automation control systems projects. The methodology is composed of a notation and a design process. New constructs will be introduced to model partitioning, timing, concurrency, and components. A component-based reference architecture truly adapted to the real needs of the industrial environment and suited for different cell configurations is developed. Metrics will be provided that allow the user to analyze the overall complexity of the final design. A new metric is presented, the Efficiency of Complexity, to measure the complexity of a implemented system normalized over its designed functionality. Two applications where this design methodology was implemented will be examined in detail. In the second case, it will also be shown to be applicable to more conventional manufacturing systems as well. With the proposed approach, many of the problems typically seen during agile control system control system software development were reduced.

Rapid Prototyping Polymer Parts Via Shape Deposition Manufacturing

Dr. John Kietzman, Doctor of Philosophy in Mechanical Engineering

Shape Deposition Manufacturing (SDM) is a novel rapid prototyping technique. It is a layered manufacturing process involving an iterative combination of material addition and material removal. Objects are built in layers by depositing and machining part materials and surrounding support materials. When complete, they are removed from the sacrificial support material, including the manufacture of assembled mechanisms and objects with embedded sensors, actuators, or electronics.

There are a variety of requirements and constraints on SDM part and sacrificial support materials, including chemical and physical compatibility, mutual adhesion, machinability, support material removability, and low shrinkage. Several material combinations were developed for use in Polymer SDM, including systems with greater ease of support material removal, systems with shorter cycle times, and systems with higher strength. Thermoset resins have been used to build a variety of parts.

SDM part strength is determined both by the bulk material properties of the part materials and by their interlayer bonding. Three thermoset resins were tensile tested – two polyurethanes and one epoxy. Both monolithic specimens and specimens with two interlayer interfaces were tested. Interlayer tensile strengths were found to vary greatly among the three materials, from 5 – 40 MPa. Relative interface strengths can vary significantly even within a class of materials. These variations may be explained by different surface wetting characteristics of the two materials.

A solution to this variation of interlayer strength is to build monolithic rather than layered parts. Polymer SDM support materials were used by other researchers to develop a variant process called "Mold SDM," in which layered wax molds are built and resins are cast into them. The moldmaking steps of this process were automated using custom machinery. A variety of parts, assemblies, and mechanisms have been made using Mold SDM.

Advanced FMEA: A Method for Predicting and Evaluating Failures in Products & Processes

Dr. Steven Kmenta, Doctor of Philosophy in Mechanical Engineering

Failure Modes and Effects Analysis (FMEA) is a technique to help anticipate, evaluate, and reduce risk of failures in a design (or process) before they occur. Although FMEA has worldwide recognition across many industries, there are documented drawbacks to the technique in practice. Some shortcomings of conventional FMEA include: a) FMEA is not effectively used during the early stages of design, b) FMEA often does not anticipate key failures, and c) FMEA employs an inconsistent risk evaluation method.

Anticipating failures early in the development process i) dramatically reduces the cost of implementing solutions, and ii) significantly improves reliability. This presentation introduces Advanced FMEA: a method to identify a more comprehensive set of potential failures, early in the development. In addition, the method introduces an improved technique for quantifying and prioritizing risk. To meet these objectives, Advanced FMEA combines the following concepts:

1. A function-state model for representing designs, systems, and processes
2. A technique for identifying failures using the function-state model
3. Using the concept of "failure scenarios" in FMEA for improved failure representation and risk evaluation
4. Risk evaluation criteria based on probability and cost

Advanced FMEA can be applied to conceptual designs, concurrent design of products and controls, manufacturing processes, and other business processes. In addition, the new risk evaluation criteria facilitate cost-based decision making during product development. The relative merits and limitations of Advanced FMEA are demonstrated through several case studies and theoretical examples.

Methodologies Used to Forecast Technologies and the Rate of Technological Change

Dr. David Monahan, Doctor of Philosophy in Industrial Engineering/Technology Management

In this study we are investigating the methodologies used to forecast technologies and the rate of technological change particularly in the fast moving high technology industries. Much of the literature and media discuss the increasing rate of technical change with little but anecdotal evidence to support these claims. This rate of change and the speed of adoption of these changes are important to businesses as they affect not only the R&D investment and strategies but also the manufacturing functional areas to plan for bringing capacity up (and down as product reaches obsolescence) as well as investment in new processes and equipment.

For the semiconductor industry, Moore's Law predicts there will be a doubling in speed and density of semiconductor devices every 18 months. Although this law predicts the abilities of the companies in the semiconductor industry it says little about whether this capability has any marketability. With the introduction of the new technology we investigate the rate of acceptance and look for methods of forecasting this change. The Technology Roadmap for 1997 from the Semiconductor Industry Association states that microprocessors have typically lagged DRAM's in technology but have closed that technology gap in the past few years. We demonstrate that the speed of acceptance of new microprocessors has dramatically increased for microprocessors over time but that DRAM's has fallen off. We also investigate the data communication market that has been said to be increasing in bandwidth at double the rate of the semiconductor industry. Using logistics curves as a basis for forecasting we develop forecasts for the various future products within these markets.

Incorporating Environmental Consequences into Design Decisions

Dr. Eva Regnier, Doctor of Philosophy in Manufacturing

Environmental consequences are involved in manufacturers' decisions in areas ranging from product design to equipment purchase. Environment-related costs are increasing as a fraction of manufacturers' total costs, and are increasingly likely to be recognized at the time of the relevant decision.

Motorola developed a design tool (the Green Design Advisor, or GDA) that evaluates the environmental impacts of alternative product designs, including end-of-life issues such as recyclability and disposal costs. My contributions included an investigation of sources of uncertainty in the GDA method, and the development of a probabilistic method for estimating data and model uncertainty in GDA calculations. In addition, I conducted a survey of life-cycle-assessment databases to estimate the uncertainty in GDA input parameters and developed and tested an improved method for eliciting stake-holder preferences for various components of environmental performance and for measuring the uncertainty associated with the measured preferences.

My experiences working on the GDA helped me to identify some of the difficult issues underlying decisions with environmental consequences, including the pervasive uncertainty and the complications in integrating multiple criteria, such as multiple environmental impacts and financial considerations---against which environmental concerns are always weighed.

Although uncertain cash flow projections are a major factor in most investment decisions, the most widely used methods for accounting for timing and risk ---discounted cash flow (DCF) methods---have shortcomings that are particularly relevant when they are applied to investments that have an environmental component. For example, most large companies use risk-adjusted discounting to compensate for uncertainty in cash flow projections. When the project's cash flow profile includes benefits followed by costs---such as product take-back costs---or risks of costs---such as environmental lawsuits---risk-adjusted discounting can lead to risk-prone decisions. The more distant the risky future cost, the greater the risk-seeking tendency induced by risk-adjusted discounting. I show this effect quantitatively and propose a modification of conventional risk-adjusted discounting for projects with uncertain future costs.

I empirically tested and found strong support for the hypothesis that environmental costs take longer to accrue than non-environmental costs, implying that risk-adjusted discounting will encourage more frequent and severe risk-prone decisions with respect to projects that involve environmental costs.

Distortion Compensation for Powder-based Rapid Prototyping

Dr. Stephen Jeffrey Rock, Doctor of Philosophy in Electrical and Computer Engineering Systems

First-generation form-and-fit Rapid Prototyping technologies have been applied to achieve substantial design cycle efficiency improvements. However, fabricating dimensionally accurate structural strength parts remains a key challenge which must be overcome to enjoy the full benefits of Rapid Prototyping throughout the product development cycle.

Powder-based processes operating on metals and ceramics have promise for meeting this need for improved strength and can be employed on a wide variety of materials. Many rapid prototyping processes have been developed or later adapted to create parts using metal and ceramic powders. However, powder consolidation required to develop desirable material properties often introduces geometric distortion which undermines the utility of resulting components.

Research was conducted to develop a methodology for geometrically compensating for process induced distortion so that material properties need not be sacrificed in an attempt to realize useful parts. Focus was given to distortion encountered in the Freeform Powder Molding (FPM) process; however, results are generally applicable to other powder consolidation-based processes. The unique temporal and economic constraints of Rapid Prototyping, combined with the wide range of materials subject to processing, motivates an unconventional approach.

A simplified sintering model was drawn from the literature and combined with a granular material model representative of a second non-consolidating tool powder as required by FPM. Key model parameters were determined by numerical investigation using a finite element model. Parameters exhibiting relatively low sensitivity were set either by simple experiment or assumption. The remaining parameters having the greatest influence on distortion were then optimized to minimize the difference between predicted distortion and that observed experimentally in a set of test specimens.

Once the model and its parameters were defined, it was iteratively applied to a new desired part shape which was ultimately transformed into process compensated geometry. A test specimen having this predicted process compensated geometry was fabricated by freeze molding and consolidated by sintering. The resulting distorted part shape was very close to the desired part geometry, and this verified the utility of the distortion compensation methodology developed in this work.

Particle and Film Growth in Fluorocarbon Plasmas

Dr. Michael Joseph Schabel, Doctor of Philosophy in Chemical and Environmental Engineering

Plasmas are used extensively in the manufacturing of microelectronic devices. In typical fabrication facilities, plasmas may be used for etching, deposition, cleaning of a substrate, and chamber cleaning. One of the major challenges to the effective use of plasmas for microelectronics processing is the formation of particles and films from reaction byproducts, which can contaminate both the substrate and the chamber. However, in other communities, the growth of particles and films in plasmas provides opportunities for the production of novel materials, for studies of astrophysical phenomena, and for macroscopic simulations of condensed matter physics. Extensive studies of particles and films in plasmas have resulted in an understanding of particle dynamics including charging, trapping, transport, and deposition. However, comparatively little is understood about the nucleation and growth behavior of particles and films. In this contribution, particle and film formation mechanisms in low-pressure fluorocarbon plasmas are discussed. It is shown that gas phase molecular growth reactions are responsible for the formation of chemical precursor to particle and film nucleation. A fluorocarbon chemical reaction library has been developed, and when used in conjunction with a plasma chemical kinetics model, gives excellent agreement with experimental observation of molecular growth reactions and particle and film formation.

Manufacturing Design for Si Solar Cell Optimization

Dr. Aimee Smith, Doctor of Philosophy in Materials Science

The Si materials system offers the most promise for terrestrial based solar cells due to its vast abundance, lack of toxicity, and its tremendous knowledge base from the integrated circuit industry. A large performance gap continues to exist between the capability of Si solar cells produced in the laboratory and those produced by high volume manufacturing. Eliminating this loss in potential can be accomplished through a manufacturing design procedure that combines scientific understanding of the losses and variations introduced in the economically constrained manufacturing environment with sophisticated systems of statistical process control. Towards this end, we have worked on the understanding of the Al back contact formation process, metal impurity gettering, and statistical monitoring in the manufacturing environment. Our work with the Al contact demonstrates that an understanding of surface stability can allow for a process design that optimizes the resulting back contact for back surface field creation and electrical contact quality. We have created a simulator to follow the evolution of transition metal impurities with the process stream, and use it in materials and process design. We have worked within the manufacturing environment with statistical methods to determine process variation that enables the separation of induced effects from process noise. The impact of these studies will be presented within the context of the rapidly expanding Si photovoltaic market.

Analysis of Thermal Distortions in Dry Drilling

Dr. Matthew Bono, Doctor of Philosophy in Mechanical Engineering

This research investigates the effects of thermal distortions of the tool and workpiece on the size and cylindricity of holes drilled without cutting fluid. A model has been developed for predicting the heat partition into the workpiece in dry drilling. An oblique cutting analysis and an advection heat partition model calculate the heat flux loads on a finite element analysis of the workpiece. Experiments using embedded thermocouples have verified that the model predicts the temperature field in the workpiece reasonably well for a range of drilling speeds and feeds.

Another finite element analysis predicts the flow of heat into the drill, and experiments using thermocouples embedded in the drill have verified the accuracy of the model. To predict the net effects of thermal distortions in dry drilling, the models of the workpiece and drill are combined. The analysis predicts that for typical industrial drilling processes, thermal distortions of the drill and workpiece lead to oversized holes with a bell shape.

The knowledge gained from this research has helped industrial manufacturers determine the extent to which dry machining will be used in the future. By revealing the magnitudes of the thermal distortions incurred in dry drilling, the research has allayed concerns of unacceptable distortions and verified that research toward designing new drills and processes for dry drilling should continue. Currently, automobile manufacturers are researching the implementation of minimal quantity lubrication techniques in their manufacturing processes.

Turning Hardened Steel with Ceramic-Coated and Uncoated PCBN Cutting Tools

Dr. Ty Dawson , Doctor of Philosophy in Mechanical Engineering

Machining hardened steels has become an important manufacturing process, particularly in the automotive and bearing industries. Abrasive processes such as grinding have typically been required to machine hardened steels, but advances in machine tools and cutting materials have allowed hard turning on modern lathes to become a realistic replacement for many grinding applications. There are many advantages of hard turning, such as increased flexibility, decreased cycle times, reductions in power consumption, and elimination of environmentally hazardous cutting fluids. Despite these advantages, implementation of hard turning remains relatively low, primarily due to concerns about the quality of hard turned surfaces and a lack of understanding about the wear behavior of polycrystalline cubic boron nitride (PCBN) cutting tools.

PCBN tools are expensive, and excessive tool wear can eliminate the economic advantage of hard turning. To address this concern, this research investigated the effect of changing process conditions on wear behavior when turning hardened AISI 52100 steel with both ceramic-coated and uncoated PCBN cutting tools. Traditional techniques of characterizing tool condition (optical and scanning electron microscopy) can provide important information about tool wear, but are generally restricted to qualitative analysis. For a quantitative study of wear, a white light interferometer was used to obtain three-dimensional images of the wear scar on cutting tools. Data from these measurements allowed quantification of flank wear, crater wear, and tool life, and wear models were developed to describe the behavior. The results of this work are allowing manufacturers to make more educated decisions about selecting process conditions, potentially enabling further replacement of grinding operations with hard turning.

Design, Operation, and Heat and Mass Transfer Analysis of a Gas-Jet Laser Chemical Vapor Deposition System

Dr. Chad Edward Duty, Doctor of Philosophy in Mechanical Engineering

Laser chemical vapor deposition (LCVD) is a new manufacturing process that holds great potential for the production of small and complex metallic, ceramic, and composite parts. However, the field of LCVD is still in its infancy and the deposition process is not well understood, especially as it relates to the manufacture of three-dimensional objects. Therefore, the current research has focused on (1) designing and developing an advanced gas-jet LCVD system, (2) understanding and modeling the effects of the gas-jet on the deposition process, and (3) using the LCVD system to deposit a ceramic (boron nitride) and a metal (molybdenum).

Various substrates and reagent mixtures were evaluated with the thermal and fluid models. It was determined that the most significant variable in the laser heating of a substrate for the LCVD process was the substrate thermal conductivity. The forced convection cooling imposed by the gas-jet reagent delivery system was also significant, accounting for a 15 to 20% change in the substrate temperature. The mass transport model predicted that the gas-jet was an effective tool for increasing the concentration of reagent gases at the surface of the substrate across all deposition regimes. The gas-jet also generated higher deposition rates and increased deposit resolution for those processes severely limited by diffusion.

Applications of an Advanced System for Inspection of Microelectronic Devices and their Interconnects using Laser Ultrasound and Interferometric Techniques

Dr. Dathan Erdahl, Doctor of Philosophy in Mechanical Engineering

The drive for smaller electronic packages has caused an increased use of surface-mounted electronic components, including solder-bumped integrated circuit devices. Inspection for device interconnection quality and structural defects is more difficult because the defects are often hidden between the device and the circuit board. Current inspection methods, such as x-ray or scanning acoustic microscopy, can probe inside a device's structure to obtain images of some defects, but they are not suitable for rapid, on-line inspection.

A new, non-contact, nondestructive inspection technique developed at Georgia Tech is capable of detecting defects such as missing, cracked, or misaligned solder bumps, open electrical connections and structural defects in the device itself. The technique uses pulsed infrared laser energy to excite a microelectronics device into vibration and an interferometer to measure the out-of-plane surface displacement. Defects in the device structure or in the solder connections beneath the device cause measurable changes in the vibration response, and signal processing techniques are used to compare vibration signatures of tested devices to a reference, defect-free device.

The long-term goal of this research is to develop a low-cost, sensitive, fast, highly automated prototype system to demonstrate how the technology could be used as a go/no-go gauge for on-line inspection or as an inspection/diagnostic tool during process development. This presentation discusses the performance of the current inspection system, presenting results for some test cases, supported by finite element models of vibration behavior. These results aid the discussion of system performance (accuracy and sensitivity) and limitations.

A Data Mining-Based Engineering Design Support System

Dr. Carol J. Romanowski, Doctor of Philosophy in Industrial Engineering

Today's business environment is one of cheap computer storage and widespread data collection. No one disputes that customer and product data is valuable, but the sheer volume, heterogeneity, and distributed nature of stored data, coupled with obsolete legacy software systems, have hindered the efficient use of this precious information. Data mining, a field related to machine learning, finds patterns and relationships in such large, multi-dimensional databases.

At present, therefore, product designers do not have easy access to product life cycle information and other critical feedback contained in stored enterprise data, resulting in costly design iterations and increased time-to-market. In variant design, where designers are reusing components and subassemblies, historical data related to earlier iterations of the product – from concept to disposal – contain crucial knowledge that can lower the total cost of product design.

This research proposes a data mining approach to incorporating heterogeneous and distributed product life cycle information, within a system framework that allows the designer to access both mined knowledge and original documentation. The complete system framework includes a data preparation module, an imaged-documents warehouse for legacy hardcopy data, a data warehouse for in-house engineering data, a data mining manager module, a conflict resolution module, a company-specific index and thesaurus, a query module that accesses enterprise-wide databases, and an information retrieval engine. The system includes an intelligent CAD system and optimization capabilities.

Energy Scavenging for Wireless Sensor Nodes with a Focus on Vibration-to-Electricity Conversion

Dr. Shadrach Roundy, Doctor of Philosophy in Mechanical Engineering Manufacturing

The vast reduction in size and power consumption of CMOS circuitry has led to a large research effort based around the vision of ubiquitous networks of wireless sensor and communication nodes. As the networks increase in number and the devices decrease in size, battery replacement becomes infeasible. It is, therefore, necessary to investigate alternative methods of powering the wireless sensor nodes. This research has focused on potential "ambient" sources of power that can be scavenged or harvested and subsequently used to run low power electronics and wireless transceivers. After a broad survey and evaluation of potential power sources, the research was focused on the conversion of low-level vibrations to electricity.

Three potential methods of coupling the mechanical kinetic energy to electrical energy exist. They are inductive, capacitive (or electrostatic), and piezoelectric. Given the constraints of the project (size, voltage, etc.), it appears that capacitive and piezoelectric converters are the most attractive. Capacitive converters are attractive because they are the easiest to implement with silicon micro-machining technology, which improves the potential for tight integration with microelectronics. While a piezoelectric implementation is more difficult to implement with micro-machining technology, it is capable of greater output power densities. Detailed models for both types of converters have been developed and used to evaluate alternative design concepts. A first round of piezoelectric prototype designs produced $75 \mu\text{W}/\text{cm}^3$ from a vibration source of 2.25 m/s^2 at 100Hz. Furthermore, the correlation between simulations and actual test results was good enough (about 15% error) to use the models developed as a basis for design and optimization. Optimized devices have been built and tested and result in an output power of $300 \mu\text{W}/\text{cm}^3$ from the same vibration source. Simulations for MEMS based electrostatic converters show power densities of approximately $75 \mu\text{W}/\text{cm}^3$. Test devices to verify these simulations are currently in fabrication.

Analysis-Enhanced Assembly

Dr. Andrew Scholand, Doctor of Philosophy in Mechanical Engineering

Several difficulties prevent the use of analyses of product physical behaviors during processing as decision support tools in process planning and control in the Electronic Assembly and Fabrication domain. These difficulties include knowledge of and access to suitable analysis models, addressing the dynamic nature of the product's transformation from raw materials to finished product, and sparse relationships between analysis boundary conditions and manufacturing resources. Both the use of and development of analyses in the manufacturing environment would also benefit from explicit representations of which manufacturing processes were represented in a given analysis, and how their effect upon the product was accounted for.

This research aims to improve manufacturing processes used in Electronics Assembly by developing a novel methodology for applying analysis in this domain. By taking advantage of the structured nature of manufacturing in the Electronics Assembly arena, an explicit quantification of the effect of process management on various measures of product quality is enabled. Thus, the manufacturing engineer utilizing this new Analysis-Enhanced Electronic Assembly representation can measure, and hence trade-off, the effects of process management on both the quality of goods produced and the manner in which his company meets customer demand. In addition, the explicit capture of expert knowledge needed for the development of manufacturing analysis models facilitates analysis accuracy, consistency, and continuous refinement and development by analysts.

This research extends research undertaken by the Engineering Information Systems Lab over the last decade to improve the methodology of analysis. This prior work includes the information architecture used to unify disparate information sources needed for analysis, and a formalism for capturing the nature of and the usage of simplifications (*idealizations*) to this data. Key extensions included an Analyzable Manufacturing Model to capture equipment and process plan information needed by analysis, and a Topic Map-based associativity meta layer above existing framework objects.

**UNITED STATES DEPARTMENT OF ENERGY
INTEGRATED MANUFACTURING & PROCESSING PREDOCTORAL FELLOWSHIPS**

Fellows Supported Under Award No. DE-FG02-94ER14474

1995

Dr. James R. Bradley
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Dr. Stewart L. Coulter
Dr. Ely Dahan
Dr. Jay P. Daniel
Dr. Richard J. Jerz
Dr. James D. Morrow
Dr. Edward P. Morse
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Georgia Institute of Technology
Stanford University
University of California, Berkeley
University of Iowa
Carnegie Mellon University
Cornell University
University of Southern California
Stanford University
University of Illinois, Urbana-Champaign
Carnegie Mellon University

1998

Dr. Antonio Alcazar
Dr. Alexander Cooper
Dr. Brad Kinsey
Dr. Sabine Vivian Kunig
Dr. Mary Kurz
Dr. Burton Lee
Dr. Mary Mahler
Dr. Joseph Napoli
Dr. John O'Brien
Dr. Barry Reed
Dr. Pete Retondo
Dr. Tony Schmitz

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University of California, Berkeley
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1995 Fellows

Managing Capacity, Inventory and Subcontracting Policies Effectively in Manufacturing Systems

Dr. James R. Bradley, Doctor of Philosophy in Industrial Engineering

Researchers and managers of manufacturing systems often address capacity and inventory decisions separately, thus ignoring the interaction between capacity and inventory. We construct three single-product, single-station manufacturing models that describe the interaction between capacity and inventory. We show that managerial approaches that do not simultaneously consider both capacity and inventory can potentially lead to a significant increase in operating cost. Furthermore, it is shown that some rules of thumb for setting capacity levels are difficult to apply and that, contrary to a manager's motivation, arbitrary reductions in capacity or inventory can increase cost. A heavy-traffic approximation is shown to accurately approximate the optimal capacity and inventory policies for manufacturing models under certain conditions. We also show that idleness is not always detrimental to the performance of a manufacturing system, even when the idle station is the bottleneck.

Disintegration of vertically integrated firms is one factor that is motivating the increased frequency of subcontracting, a practice whereby firms supplement their own production capabilities. This paper simultaneously analyzes the effect of capacity, inventory and subcontracting policies on operating cost. An optimal inventory and subcontracting policy structure for a discrete-time subcontracting model is established. A continuous-time analogue is also developed which allows more tractable analysis of the subcontracting problem. The analysis presented here is useful in making operational decisions regarding inventory and subcontracting control policies in the short term over which capacity is essentially fixed. The models are also useful in making strategic decisions because they allow inventory and subcontracting policies to be analyzed as the capacity level varies.

Reducing Environmental Impact Through Systematic Product Evolution

Dr. Stewart L. Coulter, Doctor of Philosophy in Mechanical Engineering

Whether propelled by a concern for the environment, increasingly stiff legislation, or higher disposal costs, companies are trying to reduce the environmental impact of their products. At the same time, designers are forced to achieve the same, or more stringent, design constraints in less time, balancing the need to get a product to market quickly with the desire to improve the product's functionality. Candidate designs are often so constrained that addressing redesign goals such as environmental impact reduction proves infeasible, or at least extremely difficult. However, it is postulated that an opportunity exists to address these redesign goals through an iterative revision process whereby designers can improve a design over multiple design iterations. This allows designers to produce a series of products in a timely manner while gradually approaching product goals.

In this work, a decision-based method for the creation of a systematic evolution strategy has been developed and tested to support designers engaged in the iterative redesign of an existing product. Creation and use of this strategy is intended to allow designers to gradually address new or more stringent product goals within the constraints of the redesign process for a particular product. In the development of this strategy:

- The design process is phrased in terms of the limiting factors in the existing design which must be changed to improve the product.
- The design space is defined in terms of changes to the product, restricting the number of options that a designer may search to make the problem more tractable.
- Explicit representation of uncertainty in design process information is used to make the design robust with respect to this uncertainty.

This method enables creation of a strategy for identifying which elements of an existing product are to be the focus of a redesign effort for each of several iterations based on long-term product goals and resource availability. Once developed, this method is applied to the design of automotive assemblies to reduce their environmental impact.

Parallel and Sequential Prototyping in New Product Development

Dr. Ely Dahan, Doctor of Philosophy in Operations, Information and Technology

I. Optimal Parallel and Sequential Prototyping in Product Design

When designing a new product, developers must balance the expected profit of improving the design against the cost and time requirements of doing so. We investigate this tradeoff by modeling the prototyping stage of product development as a search process. Multiple prototypes are modeled as random draws from a probability distribution. The model balances the cost of building and testing the prototypes against improvements in expected profits. We identify optimal policies for single-period and infinite-horizon problems and derive closed-form solutions for the case of discrete, Uniform and Gumbel-distributed profits. The paper compares performance of pure parallel, pure sequential and hybrid parallel-sequential experimentation policies. We present a prototype design methodology that yields the optimal combination of Bernoulli trials with varying parameters. We show how the mode of experimentation determines the preferred type of product.

II. The Predictive Power of Market Research Using Visual Depiction

We measure the predictive accuracy of Internet-based product concept testing that incorporates virtual prototypes of new products. The method employs a two-factor conjoint analysis of parallel prototypes and prices to enable a design team to select the best of several new concepts within a product category. Our results indicate that virtual prototypes on the Web provide nearly the same results as physical prototypes. As virtual prototypes cost considerably less to build and test than their physical counterparts, design teams using Internet-based product concept research can afford to explore a much larger number of concepts. In short, the Web can help to reduce the uncertainty in new product introductions by allowing more ideas to be concept tested in parallel.

III. The Profit Saddle: Optimal New Product Pricing and Cost Reduction

We construct a simple model of total profit as a function of two decisions by the firm: unit price and unit cost. The decision on unit cost takes the form of investment in design for manufacture and assembly (DFMA). Demand is modeled as a non-increasing function of price and is empirically measured using conjoint analysis. We characterize the optimal policy for DFMA investment and product pricing under several demand regimes and show that total profit may be convex in unit cost. That is, DFMA investments that result in small reductions in unit cost may have a significant impact on total profit.

In-Process Discrimination of the Ductile-Brittle Transition in Brittle Materials Machining-Theory and Experiment

Dr. Jay P. Daniel, Doctor of Philosophy in Mechanical Engineering

In the machining of brittle materials, the transition from ductile mode to brittle mode material removal occurs as the material removal mechanism migrates from plasticity dominated mechanisms to mechanisms dominated by material fracture. Differentiation of the material removal mechanism is an important factor in controlling the productivity and quality of the material removal process.

Real time interrogation of the transient acoustic wave forms generated by a material removal process is a highly sensitive probe for monitoring precision machining operations. To make such a probe more meaningful for monitoring the ductile-brittle transition, a parameter of the acoustic signature of a process that tracks the ductile-brittle transition needs to be developed. A robust signal parameter should have three properties: 1) it should be predicted by the physics of acoustic source generation and propagation for ductile and brittle acoustic sources, 2) it should be invariant to the amount of energy in the acoustic signal of a process, and 3) it should be experimentally verifiable.

A parameter that satisfies these three criteria, the high frequency displacement wave form kurtosis, was developed. The acoustic physics that predict the utility of using high frequency signal kurtosis to detect the ductile-brittle transition are first discussed. The relevance of utilizing the signal kurtosis to interrogate the ductile-brittle transition is explained.

An experiment used to test the ability of the high frequency kurtosis of the acoustic displacement wave form to detect the ductile-brittle transition is described. Results are presented showing the relationship between scratch character and signal kurtosis.

A Resource Consumption Model (RCM) for Process Design

Dr. Richard J. Jerz, Doctor of Philosophy in Industrial Engineering

Varieties of production economic models exist (e.g., return on investment analysis, break-even analysis, cost estimating, and design for manufacture) to aid production process design for product manufacture. These models, however, fail to integrate sufficiently the concepts of cost, production cycle time, production capacity, and utilization. The methodologies typically rely upon these factors being separately analyzed, but do not guarantee that they are. Some methodologies use a narrow production volume range, or worse, one production volume in their calculations, which limits additional insight into economies of scale.

The resource consumption model for process design (RCM) is the result of several years of research into better models for the analysis and selection of process design alternatives. RCM is a decision support methodology that provides greater understanding, fidelity and sensitivity analysis to process design than other techniques. RCM's foundational concept is that part production consumes resources that can be translated into cost, time, and utilization metrics. RCM accounts for all resources, which can be equipment, labor, energy, material, tooling, and other consumables used by alternative process designs. It characterizes resources generically and avoids the need for terms such as "fixed costs," "variable costs," "overhead," and so forth. For each resource, RCM performs quantity-based, time-based, and system-based calculations for a production volume range and determines the controlling condition. Resource calculations are accumulated to compare alternatives. Results are shown in both tabular and graphical formats. A computer model that uses several modern programming technologies was developed to integrate RCM concepts.

RCM concepts are applied to a manufacturing process design problem to demonstrate the method and the type of results and insights that RCM provides. A number of questions about the problem are addressed using RCM. A comprehensive modeling of process alternatives is very difficult, if not impossible, without RCM. RCM successfully demonstrates that new process design models can be developed utilizing mathematically intensive concepts and implemented using modern computational tools.

Sensorimotor Primitives for Programming Robotic Assembly Skills

Dr. J. Daniel Morrow, Doctor of Philosophy in Robotics

In this talk, I will give a very brief overview of my Ph.D. thesis research. The thesis addresses the problem of sensor-based skill composition for robotic assembly tasks. Skills are robust, reactive strategies for executing recurring tasks in our domain. In everyday life, people rely extensively on skills such as walking, climbing stairs, and driving cars; proficiency in these skills enables people to develop and robustly execute high-level plans. Unlike people, robots are unskilled -- unable to perform any task without extensive and detailed instructions from a higher-level agent. Building sensor-based, reactive skills is an important step toward realizing robots as flexible, rapidly-deployable machines. Efficiently building skills requires simultaneously reducing robot programming complexity and increasing sensor integration, which are competing and contradictory goals. This thesis attacks the problem through development of sensorimotor primitives to generalize sensor integration, graphical programming environments to facilitate skill composition, and design integration for exploiting the primitive capabilities during task design. Force and vision based sensorimotor primitives are built to provide sensor integration for task domains, not task instances. A task-level graphical programming environment provides an intuitive interface for the designer/programmer to compose the skill through a simple form of virtual demonstration. Finally, design agent representations of the primitives inside the CAD environment interact with the task model and the programmer to assist in composing the skill program. Experimental results for six different assembly tasks demonstrate sensor-based skill execution and illustrate primitive reusability.

Research in Dimensional Tolerancing

Dr. Edward P. Morse, Doctor of Philosophy in Mechanical Engineering

The output of any discrete manufacturing process contains some uncontrolled, or random, variation of geometric form and material properties. To insure interchangeable assembly and adequate function, mechanical designers specify allowable limits for this variation using tolerances. Manufacturing engineers select suitable processes and inspection techniques so that the tolerances are honored. There are many research issues surrounding the selection and specification of dimensional tolerances, and I have followed two related paths of investigation.

The first research path examines the use of statistical criteria for populations of dimensionally toleranced parts and assemblies. Popular industrial statistical criteria often assume, either explicitly or implicitly, that the underlying statistics exhibited by the part populations are normal (Gaussian). We have proposed models that suggest that the "natural" statistics of many geometric tolerances are non-normal, and have performed measurement experiments that support these models. These results prompted us to address the following two questions: 1) What is the influence of non-normal statistics on popular quality control criteria? 2) Can distribution-free statistical criteria be used for the dimensional control of parts and assemblies?

The second research path I am following addresses assembly criteria for rigid parts. A designer will assign dimensional tolerances to component parts which are sufficient for assembly – i.e. if the part tolerances are satisfied, the parts will assemble. However, if we are given a set of parts and asked "will these assemble?", we must consider the necessary conditions for assembly – i.e. those conditions that must be met for the parts to assemble. It is easy to construct simple (two-part) examples where the number of necessary conditions for assembly exceeds the number of tolerances that may (by traditional tolerancing convention) be used. My research examines dependencies which exist between the necessary conditions for assembly, and seeks to develop a taxonomy of assemblies based on a classification of these conditions.

Contour Crafting Process

Dr. Richard J. Russell, II, Doctor of Philosophy in Industrial Engineering

Contour Crafting is a new method of rapid prototyping that is under development at the University of Southern California. Contour Crafting promises to produce rapid prototypes much faster than today's commercially available fabricators and with superior surface quality. One of the challenges facing the Contour Crafting process was the selection of process control parameter levels that will result in unsurpassed surface quality (as compared with other rapid prototyping processes), at an unsurpassed build rate, and with sufficient dimensional and structural integrity. A second challenge was to develop a model that will allow for compensation of the thermal contraction of the thermoplastic fabrication material during solidification and cooling. The contraction of the individual layers during the fabrication process can result in a serrated outer surface on the build object. The contraction of a group of layers can result in a geometry which varies from the desired geometry.

A design of experiment approach was performed for determining the optimal control parameters that achieve superior outer wall surface finish, at an unprecedented build speed, and with adequate mechanical strength. An empirical model for predicting the layer by layer contraction as a function of time was developed to allow for real time compensation of the thermoplastic thermal contraction during cooling.

Competing in High-Tech: The Roles of Innovative Competence and Cost Competence

Dr. Glen M. Schmidt, Doctor of Philosophy in Operations, Information, and Technology

An analytical model is developed to gain insights into how a firm can insure that it continues to invest in appropriate new technologies. While not limited to high-tech firms, it may be viewed as particularly relevant for these companies because of the frequency of innovation (and therefore the prevalence of new technologies) in such industries.

Some firms appear to view technology leadership as separate and distinct from cost leadership. In contrast, this research suggests that a firm's success in sustaining a technology leadership position may hinge on its ability to produce the new product (resulting from the new technology) at lower cost. Such an ability is denoted as the firm's "cost competence." The model suggests cost competence, above a critical hurdle level, is essential to an incumbent firm's ability to position itself as the future dominant player. Where minor innovation is prevalent, the hurdle level is relatively higher, as compared to when drastic innovation is being pursued. The model also stresses the role of "innovative competence," which characterizes the firm's efficiency, effectiveness, and/or timeliness in pursuing new technology.

An additional key finding is that firms should search for discontinuities in the returns that accrue from enhanced competencies. By positioning itself on the "right side" of a "jump point," a firm may dramatically increase its profits as compared to what it might expect if it were only slightly less competent. These jump points arise at the point where the firm's competencies are sufficient to cause a competitive firm to decide against competing in the new technology game, or to significantly drop its investment amount. When the competitive firm foregoes its investment, it opens up the prospect of high returns for the incumbent.

Accuracy and Calibration of Conventional and Parallel Link Machine Tools

Dr. Hooman Tajbakhsh, Doctor of Philosophy in Mechanical Engineering

Dimensional accuracy is the single most important criterion used to evaluate the quality of machined parts. Increasing demand for highly accurate and inexpensive mechanical parts has led to the development of economical and efficient processes for their production. One crucial factor affecting the quality of machined parts is the accuracy of the machine tool used to produce that part. Software error compensation is one effective method for improving the accuracy of machine tools. This requires the knowledge of the machine's errors derived from empirical models or theoretical models that have been designed to either update the kinematics of the machine via software or to update the numerical control (NC) code.

The steps involved in achieving a successful software calibration scheme for a machine tool are as follows: (1) Error Modeling, (2) Error Observation, (3) Model Parameter Estimation, and (4) Error Compensation (software). This research addresses each, with particular emphasis on solution techniques for the first three steps.

The error modeling addressed in this research is associated with parallel link machine tools. A kinematic error model for a Stewart Platform-based machine tool is presented. The error analysis shows that forty-two kinematic parameters completely characterize the errors for a Stewart Platform machine tool. This error model allows for decoupling these forty-two parameters into six problems each with seven error parameters. Transmission error bounds are also developed for the Stewart Platform machine tool. These methods can be expanded to other types of parallel link machine tools.

The error observation portion of this research uses a novel gauge named the 'Plate-Bar Mechanism'. This gauge utilizes a ball-bar mechanism and is capable of measuring five error components in a circular path within the workspace. The system measures thermal errors and dynamic errors in three-axis machining centers. A simple trilateration along with a long stroke LVDT (linear variable differential transformer) is also used to measure three error components in the workspace of a parallel link machine tool.

Least squares estimation is the most common technique used for parameter identification of machine tool error models. This research presents a new criterion, which identifies the parameters based on the maximum error in the workspace. Experimental results show a 25% reduction in the maximum error over the least squares criterion. The error modeling, error observation, and error estimation techniques are then implemented on a three-axis parallel link machine tool. The final results show that successful calibration of a parallel link machine tool is possible when the research presented in this thesis is implemented.

Toward Gesture-Based Programming: Agent-Based Haptic Skill Acquisition and Interpretation

Dr. Richard M. Voyles, Doctor of Philosophy in Robotics

Programming by human demonstration is a new paradigm for the development of robotic applications that focuses on the needs of task experts rather than programming experts. The traditional text-based programming paradigm demands the user be an expert in a particular programming language and further demands that the user can translate the task into this foreign language. This level of programming expertise generally precludes the user from having detailed task expertise because his/her time is devoted to the practice of programming, not the practice of the task. The goal of programming by demonstration is to eliminate both the programming language expertise and, more importantly, the expertise required to translate the task into the language.

Gesture-Based Programming is a new form of programming by human demonstration that views the demonstration as a series of inexact "gestures" that convey the "intention" of the task strategy, not the details of the strategy itself. This is analogous to the type of "programming" that occurs between human teacher and student and is more intuitive for both. However, it requires a "shared ontology" between teacher and student -- in the form of a common skill database -- to abstract the observed gestures to meaningful intentions that can be mapped onto previous experiences and previously-acquired skills.

This thesis investigates several key components required for a Gesture-Based Programming environment that revolve around a common, though seemingly unrelated theme: sensor calibration. A novel approach to multi-axis sensor calibration based on shape and motion decomposition was developed as a companion to the development of some novel, fluid-based, wearable fingertip sensors for observing contact gestures during demonstration. "Shape from Motion Calibration" does not require explicit references for each and every measurement. For force sensors, unknown, randomly-applied loads result in an accurate calibration matrix. The intrinsic "shape" of the input/output mapping is extracted from the random "motion" of the applied load through the sensing space. This ability to extract intrinsic structure led to a convenient eigenspace learning mechanism that provides three necessary pieces of the task interpretation and abstraction process: sensorimotor primitive acquisition (populating the skill database), primitive identification (relating gestures to skills in the database), and primitive transformation ("skill morphing"). This thesis demonstrates the technique for learning, identifying, and morphing simple manipulative primitives on a PUMA robot and interpreting the gestures of a human demonstrator in order to program a robot to perform the same task.

1998 Fellows

Fabrication of Ceramic Components for Gas Turbine Engine Application

Dr. Alexander Cooper, Doctor of Philosophy in Mechanical Engineering

The manufacturing process that I developed to enable the fabrication of geometrically complex, structural ceramic components for use in gas turbine engine applications is called Mold Shape Deposition Manufacturing (Mold SDM). It uses layered manufacturing techniques, similar to many rapid prototyping processes, to build complex shaped fugitive molds. The molds can then be cast using a wide range of low temperature, low pressure castable materials such as gelcasting slurries (for ceramics and metals) and polymers. Gelcasting is a slurry-based process for forming green parts and can be used with either ceramics or metals. The green parts are then sintered at high temperatures to produce fully dense, functional parts. The capability to produce complex structural ceramic components will enable improvements in efficiency, thrust to weight ratio, and operating lifetimes for gas turbine engines.

I extended the SDM process by switching to the fugitive mold-based approach and combining this with ceramic gelcasting to create Mold SDM. This necessitated switching to a different materials system that involved testing a wide range of potential combinations. Chemical compatibility between various materials was one of the most challenging issues because ceramics are very defect sensitive. Incompatibilities will usually cause defects that greatly reduce the strength of the parts.

New build techniques were developed and incorporated into the process to increase the quality of parts produced and extend the range of features that could be built. Together these build options have created a spectrum of process options that are suitable for prototyping to production uses. Depending on the particular needs, one can select among the process options to tradeoff between flexibility and efficiency.

Efforts were made to minimize build time and cost with the goal of commercializing the process, which is now capable of producing quality ceramic components with very complex shapes. These parts could not be made using other processes, so this work has created new manufacturing capabilities. I am currently working to commercialize this technology to manufacture parts for our industrial sponsors.

A Combined Approach to Improve and Assess the Formability of Tailor Welded Blanks

Dr. Brad Kinsey, Doctor of Philosophy in Mechanical Engineering

Tailor Welded Blanks (TWBs) are fabricated by welding together two or more metal sheets of different thicknesses and/or material grades to produce a single blank, which is subsequently formed into the desired geometry. By consolidating parts, this type of blank offers the automotive industry an excellent opportunity to reduce manufacturing costs, decrease vehicle weight, and improve the overall quality of sheet metal stampings. However, tearing near the weld seam often occurs when a traditional forming process is used to fabricate TWBs due to decreased material properties in the heat affected zone of the weld and the thinner, weaker material undergoing a majority of the deformation during the forming process. To address this tearing concern, the Advanced Materials Processing Laboratory at Northwestern University proposed a modification to the deep drawing process where a segmented die with local controllers creates an additional material constraint adjacent to the weld seam in the forming area. This innovation reduces the strain in the thinner material near the weld seam by forcing the thicker material to undergo more of the plastic deformation and increasing the material draw-in of the thicker material from under the binder ring. In this presentation, numerical simulation and experimental results will be presented demonstrating the exceptional ability of the advanced segmented die forming process to alleviate the potential of tearing failure thereby allowing a 20% increase in the potential forming depth for a non-symmetric test panel. Also, an analytical model to predict the weld line movement and failure height of a 2D cross-section of a TWB will be presented.

Flexible Flow Line Scheduling with Sequence-Dependent Setup Times

Dr. Mary Beth Kurz, Doctor of Philosophy in Systems and Industrial Engineering

This research focuses on flexible flow line scheduling with sequence-dependent setup times. A flow line is a collection of machines arranged in serial that each perform a unique operation. Each machine can be called a stage. In our problem, more than one machine may exist at each stage, perhaps due to a large demand for processing at that stage; we assume that the machines are identical in capability and all other operating characteristics. Jobs flow through the stages in a linear fashion, so that jobs visit the first stage, then the second etc for processing. However, this is a flexible flow line because jobs may skip stages. Between processing two jobs on a machine, sequence-dependent setup times exist. This is the time required to setup for the next job from the current job, assumed to depend on the order of the jobs and the particular jobs in question. These types of setups exist in industries such as printing and the manufacture of printed circuit boards. In this research, our goal is to schedule jobs in a system such as the one described above to minimize makespan, which is the completion time of the last job to be scheduled. A schedule's makespan can be used, for example, to determine if a given amount of work can be completed in a single shift. This research has focused on heuristic methods to schedule jobs in flexible flow lines with sequence-dependent setup times. Two approaches have proved to be most promising: a Johnson's Rule Based approach and a random keys genetic algorithm approach.

Federated Diagnostic Modeling and Reasoning For Complex Modular Products

Dr. Burton H. Lee, Doctor of Philosophy in Mechanical Engineering

Increasing downtime costs of complex equipment and products are motivating manufacturers to reassess the importance of remote diagnostics. Key to effective diagnostics is the construction of computer-based diagnostic models that simulate error and fault diagnosis conditions. These models are typically built either by customer support or research organizations, depending on model complexity. Current diagnostic modeling approaches, however, are costly and difficult to scale for highly heterogeneous product populations.

This research proposes and demonstrates a new method for reduced-cost, scalable diagnosis of modular systems. The approach leverages product modularity to 1) share diagnostic modeling efforts between OEMs and suppliers, 2) link distributed ("federated") OEM/supplier diagnostic servers in a system-level diagnosis network, and 3) reuse supplier component models in OEM diagnostic reasoners. A prototype diagnostic "Broker" has been designed and developed which connects and integrates Bayesian network supplier diagnostic models for subsystem components with an OEM system-level diagnostic model. The result is a diagnostic system that leverages supplier design expertise in the construction and maintenance of component diagnostic models, while concurrently providing a framework for the integration of such models into a full product diagnostic system. The Broker approach employs a three-tier architecture in which the background complexity of the diagnosis process is hidden from the front-end client by the middle-tier Broker. The demonstration system is authored in Java. Applications considered include motor vehicles and printers.

Bonded Repair of Composite Structures

Dr. Mary Mahler, Doctor of Philosophy in Mechanical & Aerospace Engineering

With the increased usage of composites comes the increased need to repair these structures when they are damaged. Currently, bonded repair methods are in place and restore the structure to its original strength. These methods are time consuming and require a lot of attention to be given to the manufacturing and design details.

In the design stages of the repair, there are many variables that significantly impact the strength. Understanding the impact of these variables can lead to a more robust and enduring repair. Testing these variables with a range of experiments is also time consuming and expensive. This work focused on evaluating the parameters from an analytical point of view.

To create consistent finite element models, a program was written using PATRAN Command Language (PCL) to create models that allow the user to vary the design variables of a bonded repair. The analysis was verified by correlation to existing data. These models were then used to evaluate the effect of design variables such as the taper angle, ratio of damage size to the size of the panel, and several others. The objective of this parametric study is to allow the designer an insight to make better composite bonded repairs.

The impact of variables, be thermal or structural, are more important in a developing technology area than the exact numbers of results. Understanding the trends of the vast number of variables can lead to better and alternative designs. This research hopefully will challenge the established guidelines to repair.

Communication Strategies for Co-Operating Machine Modules

Dr. Joseph T. Napoli, Doctor of Science in Systems Science and Engineering

In this research, controllers were constructed that limit and route the flow of information in a network of machine modules. The optimization of communication permits faster sampling with sensors and increased stability of controllers. This adds flexibility to reconfigurable workcell environments, particularly amongst co-operating machine modules. This research addresses point to point networks, such as a network of fixed, co-operating manipulators as well as broadcast networks, such as a fleet of mobile vehicles.

The flow of information between machine modules can be modeled with a system of ordinary differential equations. In the special case of single destination routing, a finite time optimal control problem can be formulated with this model along with a cost criteria that rewards throughput and bandwidth efficiency while penalizing time delay. This finite time problem can be solved for controllers that optimally limit and route information flow in the network.

These controllers can be generalized for multiple destinations and extended to an infinite time horizon via receding horizon control. Generalizing the controllers to the multiple destination case requires an approximation to the dynamics to keep the problem computationally tractable. This approximation in itself is significant because flow models are, in general, poorly suited to multiple destination flow. Receding horizon controllers are constructed by repeatedly solving the finite time problem at every instant. The stability of this procedure for the information flow model is shown.

Feasible Solutions to Kinematic Instability in Parallel Robots

Dr. John F. O'Brien, Doctor of Philosophy in Control Systems and Robotics

Robot kinematic research is moving away from serial arms, a field that has largely exhausted itself, into the realm of cooperative robotics. This trend is driven by stringent task space accuracies required for precision machining, micro-assembly, and accurate pointing applications that common serial chain mechanisms are ill-equipped for due to their intrinsic flexibility and accuracy reductions due to cumulative joint error.

The advantages associated with parallel robots do not come without cost. Multiple contact points on the end-effector result in mechanisms that have more restricted workspaces than their serial counterparts. A perhaps more severe shortcoming is the complexity of the parallel robot's kinematics. Constraints associated with multiple end-effector contacts usually result in no closed-form solution for the forward kinematic problem, and a complex Jacobian. The latter characteristic complicates direct analysis of the manipulability Jacobian to a priori determine the existence and location of mechanism singularities. This is further compounded by an additional set of constraints associated with the existence of passive joints in the mechanism, a trait shared by almost all parallel robots. This additional constraint has the potential for a second and more potentially destructive type of singularity, referred to in this work as unstable singularity, whereby certain task wrenches cannot be resisted by the mechanism.

This work addresses the characteristic of unstable singularity in parallel robots and multi-fingered grasps. The absolute and differential kinematics of parallel robots with passive joints are presented, and are used to develop a new method to determine the existence of unstable singularities in a given mechanism's workspace. A novel method to eliminate the unstable singularity condition is proposed, and is compared to the redundant actuation technique. The dynamics of parallel robots with passive joints are investigated, and the effect of unstable singularity on the equations of motion is assessed. This is used to develop a dynamic control paradigm for parallel robots with passive joints. Computer models of several three and six degree-of-freedom mechanisms are used to support the analysis.

Planar-flow Spin Casting: Momentum Transport, Vorticity Transport, and Texture Formation

Dr. Barry L. Reed, Doctor of Philosophy in Chemical Engineering

The planar-flow spin casting (PFSC) process is attractive to both industry and science. Industrial interest comes from novel microstructures and cost savings possible using PFSC. Scientifically, PFSC provides a test bed for studying phenomena such as the microstructure and contact lines where different materials and phases meet. These areas are not fully understood, and the interaction between industry and science is beneficial to both. A general understanding of how the ribbon thickness in PFSC depends on processing parameters exists. A broad goal of this work is to extend that understanding by considering 'second-order' effects on the process.

First the effect of viscosity is considered. A momentum transport model is developed using a boundary layer structure for the flow. The equations are averages across the narrow gap. Solidification changes the nature of one boundary layer from a classical Blasius layer to a suction-type layer. The analysis provides a prediction of the pressure field for comparison to experimental results. The model also includes vorticity in the bulk flow. A study of vorticity transport in boundary layers follows. Together these two models are establishing a base flow for PFSC. This base flow is necessary to further study issues in contacting and stability.

The importance of stability is seen in the quality of the as-cast ribbons. The ribbon exhibits various surface textures that are thickness variations occurring over small length scales. Textures are the result of flow or solidification instabilities. Two textures seen in experiments are presented. The textures are related to processing conditions to uncover possible sources. The results suggest areas to investigate and what additional data is needed.

Finally, the modeling is supported by experimental data. Important changes made to the existing apparatus are outlined. The impact of the improvements is demonstrated via experimental results. Besides better reproducibility, an emphasis is placed on simplification of the casting procedure. The final state of the caster is such that new researchers may begin to produce reliable data without difficulty.

Mechatronics and Flexible Specialization for Architecture, Engineering and Construction: Harnessing the New Paradigm in Manufacturing to Change the Way We Design and Construct Buildings

Dr. Pete Retondo, Doctor of Philosophy in Architecture

The construction of buildings has long been considered a holdout from the industrial revolution. In the early part of the 20th century, many felt it was only a matter of time before the example of Ford's mass-production assembly line would be adopted by the Architecture, Engineering and Construction (AEC) industry. Most attempts to bring about this change have ended in failure or the kind of economic eddy occupied today by the mobile home industry. Conventional wisdom has reversed its assessment to hold that the industrialized fabrication of buildings is not feasible. A closer examination shows that this history of failure is the history of a mismatch between inflexible systems of production and a market that demands a high level of variation in the product.

As mechatronic capabilities have spawned a "second industrial divide," marked by integrated manufacturing, flexible specialization, mass customization and manufacturing agility, the means for resolving this mismatch appears to be at hand. In a step towards imagining the form and impact of this new kind of industrialization on the AEC process, a set of principles for the technological shift are derived from an analysis of trends in innovative structural steel fabrication, and current CNC and CIM processes. These principles are applied to create a model of a flexible, automated system for the production of the "Smart Roof," a factory-produced roof designed to accommodate a large variety of building configurations. Four free-form and feature-based fabrication processes are proposed. An *ad hoc* integrated software environment, that projects objects "upstream" from the fabrication process control system to create user-interface program extensions for architects and engineers, is proposed as an alternative to the concept of universal software interoperability through a neutral datafile format, as envisioned by standardization efforts such as ISO 10303.

The Implementation of Simultaneous Trilateration to Measure Dynamic Three-Dimensional Contours Using the Laser Ball Bar

Dr. Tony Schmitz, Doctor of Philosophy in Mechanical Engineering

Computer numerically-controlled (CNC) multi-axis machine tools are an integral part of modern manufacturing. These machines operate in an overall open-loop mode (i.e., although the positions of the individual axes are servo-controlled, the actual spatial coordinates of the tool or end-effector are unknown). Since the machining process is open loop, the ability to monitor the cutting tool/workpiece positional relationship and predict the final part dimensions is limited.

At this time there are no pre-process measurements that can be performed to accurately predict the final dimensions of a machined part. This produces a fundamental gap in the ability to model the machining process. Although static measurements may be performed on a given machine tool to characterize its (static) positioning accuracy, the final part dimensions are a function of the machine tool's dynamic spatial positioning accuracy. A tool that could dynamically measure the tool position along three-dimensional contours to micrometer accuracy would close this gap and permit rapid verification of CNC part programs.

This research describes the design, construction and verification testing of a sensor, the Simultaneous Trilateration Laser Ball Bar (STLBB) system, which has the capability of measuring 3-D contours to micrometer-level accuracy. The verification testing includes comparison to an independent dynamic measuring device (optical grid encoder) and an evaluation of both the static and dynamic repeatability of the STLBB system. The inaugural measurement of arbitrary, 3-D dynamic path paths is also included. The data obtained from the 3-D measurements is useful for the evaluation of the controller performance during contouring and the measurement of the relative contributions of both quasi-static (geometric) positioning errors and controller errors to the part dimensional inaccuracies.