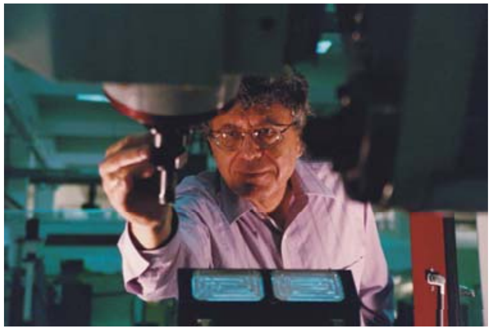
The Sixth S.M. Wu Distinguished Lecture in Manufacturing Science



From Machine Control to Manufacturing Systems Research

Yoram Koren

November 17, 2011

My Contributions are in Three Areas

1969 - 1994: CNC and Process Control

- Establishing the science base of this field (70 papers; 2 books)
- Interpolators; control loops; adaptive control
- Tool wear modeling and optimization

I met Prof. Wu in 1970 In Norway; I presented a paper on this topic.

1979 - 1992: Robotics and Mobile Robots

- Algorithms for obstacle avoidance (a paper w 1200 citations)
- 1st snake robot, 1st inflatable robot
- Wheelchairs with adaptive control & obstacle avoidance

1994 - 2011: Reconfigurable Manufacturing Systems

- Conceiving and establishing the science base of RMS
- Optimal configurations for responsiveness
- Bringing science to the factory floor – systems, inspection . . .

North American Metalworking Research Conference (NAMRC)

I met Prof. Wu in 1973 at NAMRC,

May 14-15, 1973, McMaster University, Hamilton, Canada

Volume 3. Statistics in Production Engineering, Grinding and Machine Tools

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From Sep 1974 - 1975 I was at UW, Madison

Fall 1974, Home of Prof. and Mrs. Wu, Madison

My Early Career

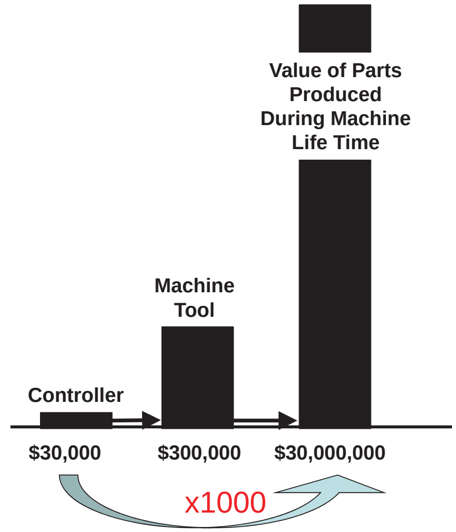
I graduated in 1965 with B.Sc. in Electrical Engineering with concentration in Control, and decided to go to grad school.

My goal was to perform research in a field that merges theoretical research with industrial relevance.

The first Numerical Controlled (NC) machines were built in the U.S. in the late 1950s.
In the late 1960's NC was an emerging interdisciplinary field.
. . . Around 1970 Computerized NC (**C**NC) machines were introduced
A scientific base for controlling NC or CNC machines did not exist;
only a few researchers had an interest in this field

Timing was perfect for CNC research

The Economic Impact of Controllers



Control of Machining Processes
by Ulsoy & Koren, ASME Trans. 1993. See:
http://sitemaker.umich.edu/ykoren/papers

My Research in CNC and Process Control

Goals: 1. **Part Quality**: Precise parts for high-quality products

2. **Productivity**: The highest processing rate without violating constraints

1. Precision:
   - Interpolators
   - Control Loops
   - Cross-coupling
   - Smart Boring

2. Productivity:
   - Adaptive Control
   - Tool Wear Modeling

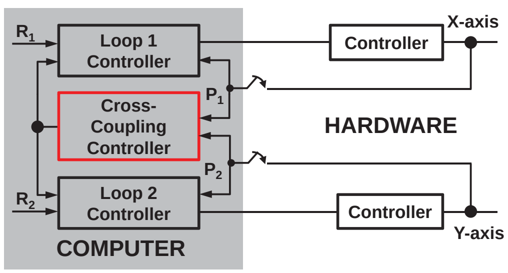
3. Optimal locus:
High productivity
subject to quality constraints

Research issues – Examples

* Coordinating motions of separately driven axes for creating precise contours
* Minimizing overshoots in corner cutting
* Maximizing productivity subject to constraints measured in real-time
* Optimal locus for highest productivity while maintaining constraints (e.g., surface finish)

Published 70 papers on these topics from 1969 to 1999

Cross Coupling Control



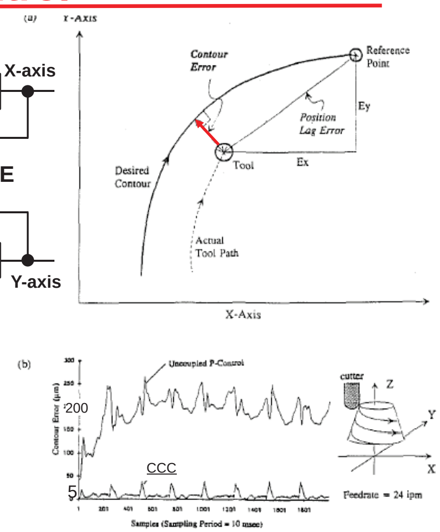
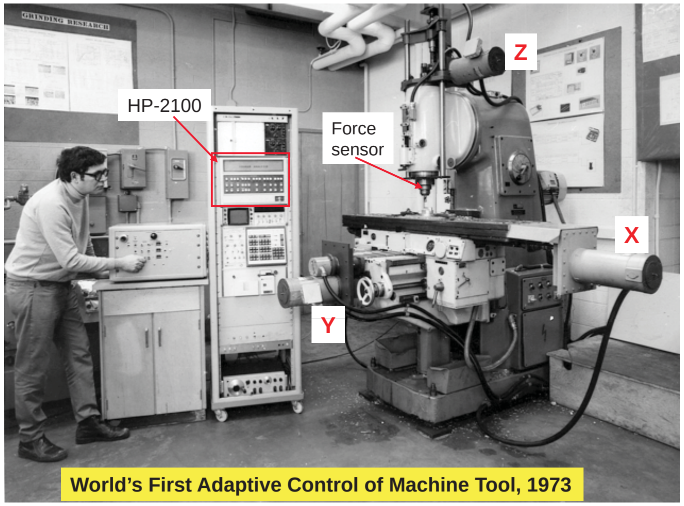


Fig. 3 Contour errors and cross-coupling control (CCC)
(a) Definition of the axis errors (Ex and Ey) and the contour error in the two-axis machining
(b) Experimental results showing the contour error in three-dimensional conical milling for an uncoupled P-controller and the CCC

Coordinating motions of separately driven axes for creating contours

Adaptive Control



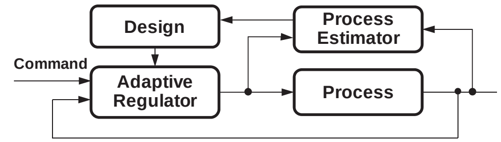
World's First Adaptive Control of Machine Tool, 1973

The control computer of both the CNC and the AC was Hewlett-Packard HP-2100. It was a 16-bit computer with a 4K memory, cycle time of 1 microsecond, and 16 I/O slots that were used to send signals to the three control loops and obtained signals from a sophisticated force sensor mounted on the spindle (the force sensor was designed by professor J. Tlusty).

Adaptive Control Optimization

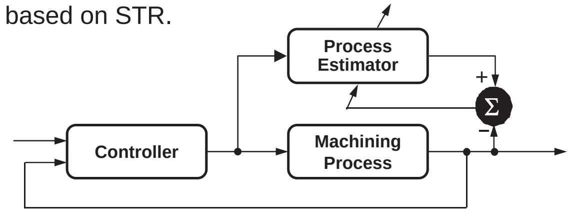
Adaptive control: A controller adapts its parameters in order to meet a given goal.

Self –Tuning Regulator (Karl Astrom 1973)

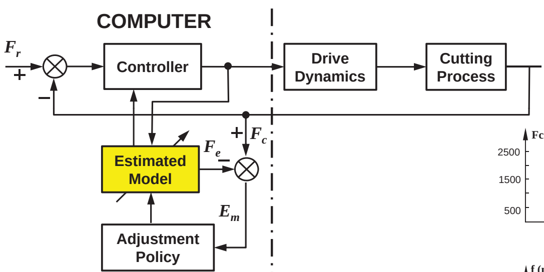


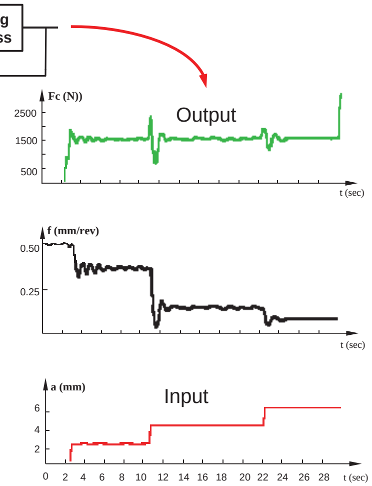
The process is known, but has unknown parameters.
Parameters are estimated in real time using recursive estimation methods.

In manufacturing we developed an "Adaptive Control Optimization" that is based on STR.



Adaptive Control for Turning



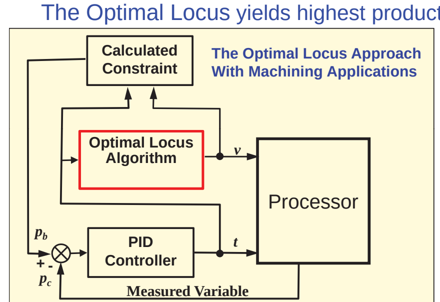


AC for
- Milling (1973-4 w Tlusty; 1980-82 w Ulsoy)
- Turning (1976-1980 w Oren Masory)
- Grinding (1977-1980 w Malkin & Amitai)
- ECG (1976-1979 w Shefi)

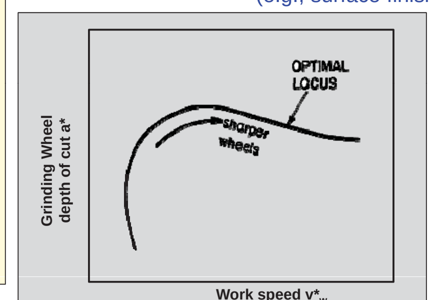
http://sitemaker.umich.edu/ykoren/papers_by_topic

Optimal Locus Example

The Optimal Locus yields highest production rates while maintaining required constraints (e.g., surface finish)



The intelligent Machining Controller (IMC)



Off-Line Grinding Optimization with a Micro-Computer

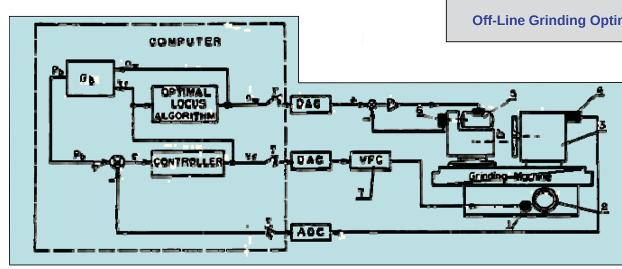


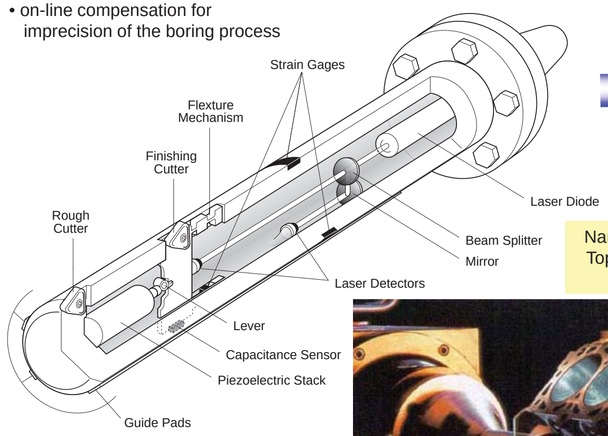
Fig.5 On-line adaptive control system
1 – stepping motor infeed drive
2 – infeed control hand wheel
3 – grinding wheel motor
4 – power sensor
5 – workpiece spindle DC motor
6 – tacho-generator
7 – voltage-to-frequency converter

Smart Line Boring Station 1994-1997

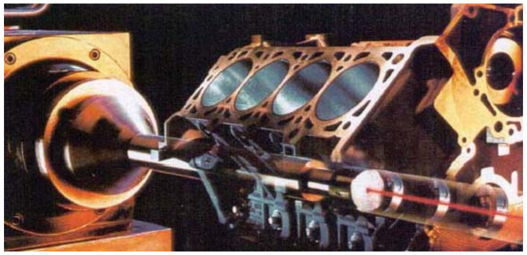
"Smart" Tool
- sensing and intelligence built into the tool
- on-line compensation for imprecision of the boring process

PI's: Koren and Ulsoy
Researchers: Pasek, Min, Segall

Mechatronics at its best



Named *Industry Week* magazine's Top 25 Technology Developments for 1999



U. S. Patent # 6,062,778

NSF-Sponsored Eng. Research Center for Reconfigurable Manufacturing Systems

Established on August 1, 1996

First ERC in the College of Engineering (the ERC Program started at NSF in 1984)

The ERC-RMS was a partnership between government, academia, and industry to identify transformative research aimed at adapting manufacturing technologies to the challenges of the 21st Century

Timing was good for RMS research

In 1995 the auto industry started to look for new technologies for adapting factories to globalization challenges.

And, the auto industry was strong.

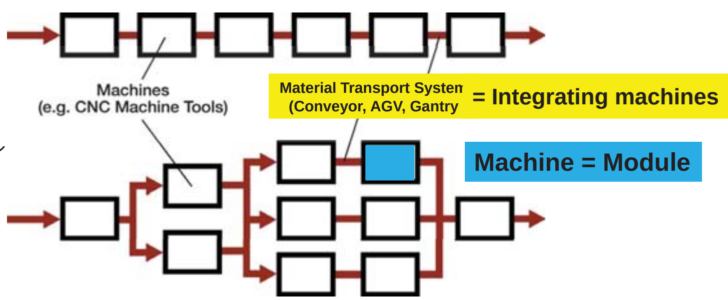
Total support from industry during 1996 – 2009 was $10 million

According to NSF, the ERC-RMS had the largest industry support (benchmark all ERC's)

ERC Topic: Multi-Stage Mfg. Systems

Systems are modular, and integrated by conveyors, etc.

Examples



A machining system in industry may include 120 CNC machines

How to organize a Research Center with 20 professors, 40 graduate students, 10 post-docs, 40 undergrad students and staff

Jacob's Dream – a Model for Visionary Research

Jacob's Dream in the Bible [Genesis Chapter 28; #12]:

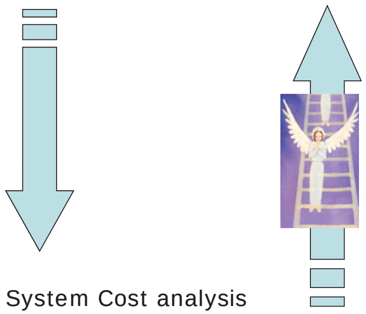
"And Jacob dreamed that there was a ladder set up on the
and the top of it
and the of God were ascending and descending on it."

Example:
Prof. Wu's 2 mm project

RMS Strategic Research based on Jacob's Dream

"And Jacob dreamed that there was a ladder set up on the earth, and the top of it reached into heaven, and the angels of God were ascending and descending on it."

Heaven = * Responsive Factories at Low Cost
* High Quality Products

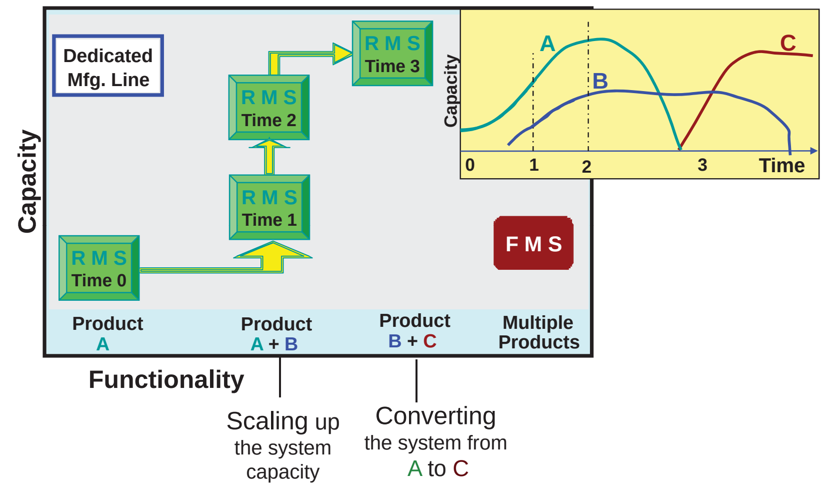


Angels connecting the heaven with earth

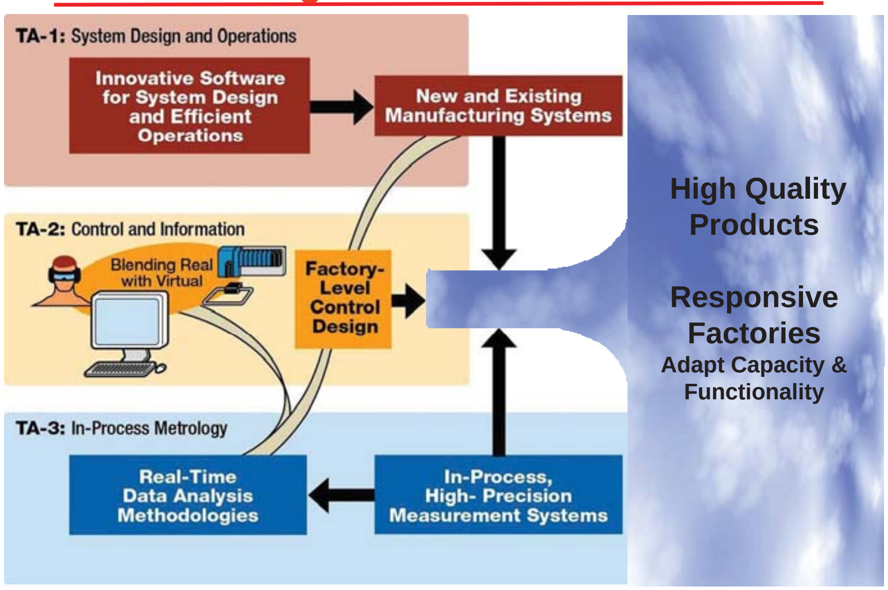
Earth = System Cost analysis
System design software
Sampling rate in control networks
In-process inspection
Maintenance decisions in large systems

Responsiveness: Adapting Capacity & Functionality

The RMS can change in response to markets



Research Organization



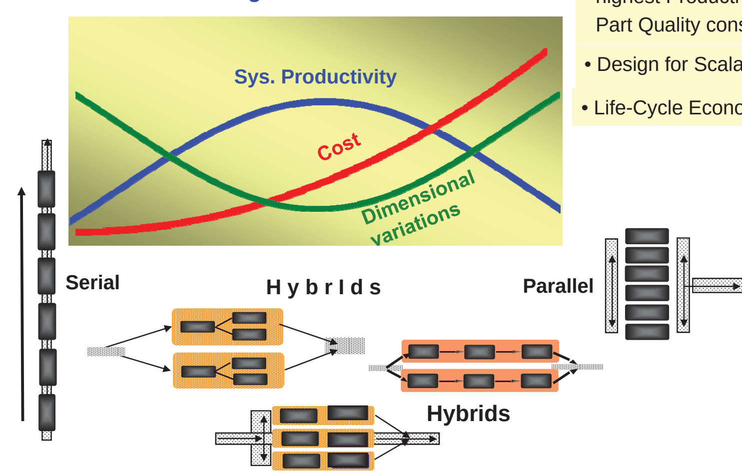
System-Level Design

A large number of possible configurations

Example: For *6* machines, there are 52 configurations

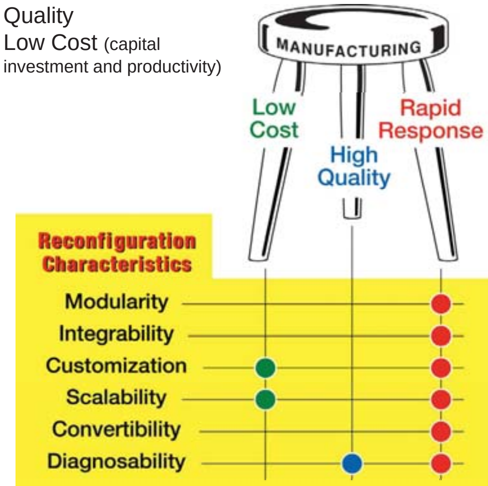
Examples of Research Issues:

- Candidate configurations with highest Productivity subject to Part Quality constraints
- Design for Scalability
- Life-Cycle Economic Model



New Goal: Responsive Systems

Traditional Goals:
Quality
Low Cost (capital investment and productivity)

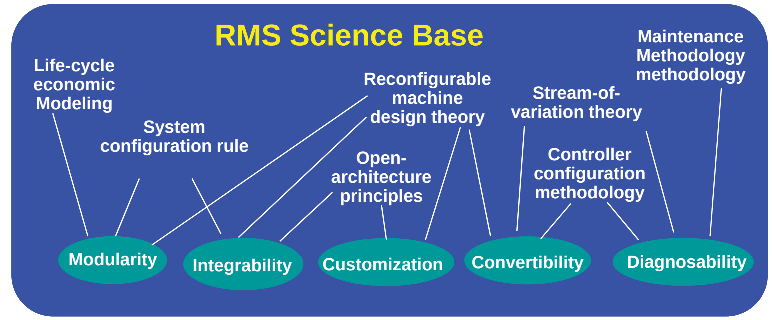


Responsive to:
- Opportunities for new products
- Demand Change
- Customer Needs
- Mfg. System Disruptions

Reconfiguration enables responsiveness

RMS Science Base

A set of theories and laws that are applicable
to the synthesis and analysis of RMSs
and share **key characteristics**



Innovative Software and Hardware

- **SHARE software for automatic line balancing**
- Utilized by GM

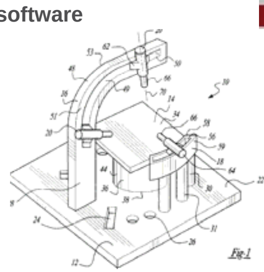
- **PAMS Software for Mfg. System Design, Optimization, Throughput Evaluation**
- Utilized by GM and Chrysler

- **Life-Cycle Economic modeling software**
- Utilized by Ford

- **Capacity Management software for designing optimal capacity**

- **Reconfigurable Inspection Machine (RIM)**
- **Cylinder bore inspection Machine**
- **World-First Reconfigurable Machine Tool**

Prototype presented at IMTS (Chicago) 2000



Reconfigurable Machine Tool Patent # 5,943750

The role of Prof. G. Spur

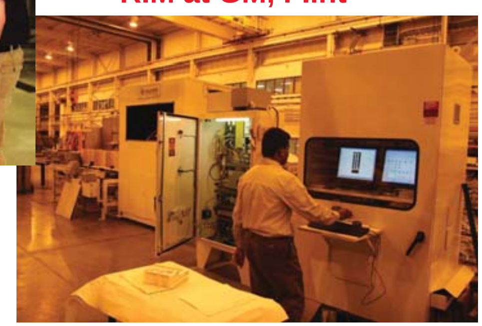
Tech Transfer – Example RIM

. . . Bringing Science to the Factory Floor . . .

RIM = Reconfigurable Inspection Machine

RIM at GEMA, Dundee

RIM at GM, Flint

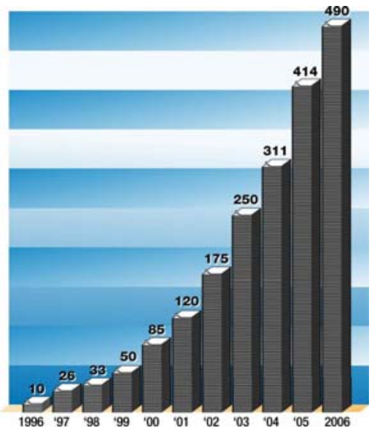


Impact – Creating a New Scientific Field

The ERC is holding 12 US Patents on:

- Reconfigurable Machine
- Reconfigurable System
- Reconfigurable Controller
- Reconfigurable Inspection Machine
- Reconfigurable Illumination for Inspection
- Reconfigurable Multi-Spindle Apparatus
- Reconfigurable Automatic Tool Changer
- Reconfigurable Power Spindle
- Integrated Reconfigurable System
- Reconfigurable Inspection for Surfaces
- Bi-Axial Co-Planar Apparatus
- Measuring Angular Alignments

Creating a new research field



Number of papers that include "Reconfigurable Manufacturing"

On 11/11/11 the number was 4111 papers

Education & Outreach

Create an awareness of manufacturing as a career

Research Experience for Undergraduates coming from other universities
Detroit Area Pre-College Engineering Program)
Museum Project
Portable Manufacturing System

Develop next generation of manufacturing leaders

Systems view
Multidisciplinary team work
With industry
Communications skills
New books and teaching material

Future: Market-of-One Products Create Jobs

Domestic Jobs How to create a job?

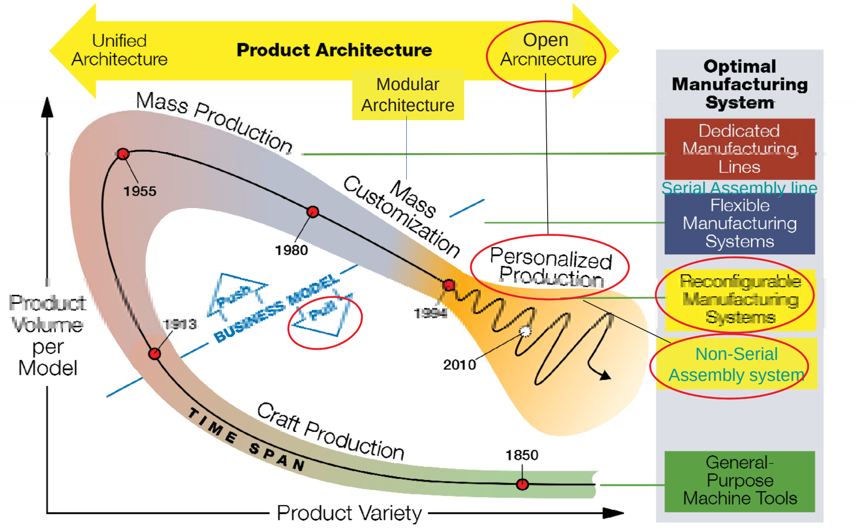
Jobs are generated by creating something that a person needs

Personalized Pro
Market-of-One at short delivery ti

Open-Architecture Platforms (mechanical, electrical)
Applications (auto interior; rehabilitation; appliances)
Product Design for Modularity
Low-cost Personalized Manufacturing

From the Book: "The Global Manufacturing Revolution"

Paradigm Transitions Over Time



Conclusion of the Sixth S.M. Wu Distinguished Lecture in Manufacturing Science

"Manufacturing was, is, and shall remain the foundation of a strong economy.

No other sector can replace it.

Without a solid manufacturing base, the service and finance sectors will collapse."

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