Advanced Manufacturing: The Key Role of Sensing, Measurement and Process Control

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Outline

• The US Advanced Manufacturing Partnership (AMP)
• AMP 1.0 Report: Central Role of Process Control
• Measurement and Control in Manufacturing
  – Process Level Control
  – Factory Level Control
  – Supply Chain and Distribution Control
• New Technology and New Opportunities
• The MIT “PIE” Study and Implications for Urban-Based Manufacturing
The Advanced Manufacturing Partnership

- Result of 9 Month Study Led by Industry and Universities with Government Facilitators

- Five Key Areas:
  - Technology Development
  - Shared Infrastructure and Facilities
  - Education and Workforce Development
  - Policy
  - Outreach

- AMP 2.0 Underway for Implementation
The “Top Ten” Technologies

- Advancing Sensing, Measurement, & Process Control
- Advanced Materials Design, Synthesis and Processing (Includes nanomaterials, metals, coatings and ceramics)
- Visualization, Informatics and Digital Manufacturing Technologies
- Sustainable Manufacturing
- Nano-Manufacturing
- Flexible Electronics Manufacturing
- Bio Manufacturing and Bioinformatics
- Additive Manufacturing
- Advanced Manufacturing & Testing Equipment
- Industrial robotics
- Advanced Forming and Joining Technologies
Advanced manufacturing is not limited to emerging technologies.

Rather, it is composed of efficient, productive, highly integrated, tightly controlled processes across a spectrum of globally competitive U.S. manufacturers and suppliers.
Why Sensing and Control?

- Cross-Cutting all Industries
- Vital to Emerging as well as Mature Technologies
- Applies to All Levels of Manufacturing
  - Machine
  - Process
  - Factory
  - Supply Chain
  - Distribution
  - Disposal

- Significant Changes in Enabling Technology
What is Sensing and Process Control

• Big Data?
• Analytics?
• Digital Manufacturing?
• Internet of Things?
• Big Brother?
• ...

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What is New?

- Concepts of Measurement & Control?
- Objectives of Measurement & Control?
- Need for Measurement & Control?
- Cost of Measurement & Control?
- Connectivity and Measurement & Control?
What is New?

• Concepts of Measurement & Control?
• Objectives of Measurement & Control?
• Need for Measurement & Control?
  — Greater Precision
  — Smaller Dimensions
  — More Complex Operations
• Cost of Measurement & Control?
• Connectivity and Measurement & Control?
What is New?

• Concepts of Measurement & Control?
• Objectives of Measurement & Control?
• Need for Measurement & Control?
• Cost of Measurement & Control?
  – Mass Implementation Means Better Technology and Lower Cost
• Connectivity and Measurement & Control?
  – Ubiquitous “Internet of Things”
What is New?

- Concepts of Measurement & Control?
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- Connectivity and Measurement & Control?
  - Ubiquitous “Internet of Things”
What is Process Control?

• Reduction of Uncertainty
  – Machine Operation
  – Process Output
  – Production Line
  – Factory
  – Supply Chain
  – Distribution
  – ...

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What is Process Control?

• Ubiquitous Feedback Control
  – Elucidation of Target
  – Measurement of Outputs and States
  – Quantifying Deviations
  – Taking Corrective Action
Which One is It?

- Ideal: All Processes Exactly on Target at All Times
- Reality: Cannot Measure or Control Everything
- Compromise
  - Measure Key Accessible Variables
  - Characterize Variation from Target
  - Take Action to Reduce Variation
The Role of Sensing?

- Data Reduces Uncertainty
- Sensing is Limited by
  - Access
  - Resolution
  - Speed
  - Accuracy
  - Cost
History of Manufacturing Process Control

• Pre-19\textsuperscript{th} Century
  – Primarily Craft Industry – Craftsman Self-Feedback
  – No Need for Standards

• Rise of “Inter-changability”
  – Enabled by:
    • Measurement and Control
    • Process Standards
  – Limited to Unit Processes
Process Control in Manufacturing

• Early 20th Century – Mass Production
  – Large Volumes – High Rates
  – No Time to “File to Fit”
  – Process Knowledge Limited

• The Shewhart Hypothesis
  – Arose from Needs in Telephony
  – Inspired by Emerging “Quantum Mechanical” View?
  – Control Means Only Random Behavior (?!)

Applying Statistics to Manufacturing: The Shewhart Approach

A Process “In-Control” is Purely Random

Use Measurements to Detect This State

Any Deviation is Cause to Investigate and Improve.

Process Control in Manufacturing

• 1950’s: Applying “IT” to Manufacturing
  – Emergence of Programmable Machines
  – Marriage of Electronics and Servo Control
  – Early Use if Digital Technology

• Measure and Control the Machine but Not the Process
  – Reduction of Machine Uncertainties
  – Loss of Product Sensing and Control
  – Limited to Certain Classes of Processes
Automation ≠ Process Control

Control of **Equipment**:  
- Motion (Forces, positions)  
- Temperatures  
- Pressures …  
aka **AUTOMATION**

Control of **Material**:  
- Strains  
- Stresses  
- Temperatures,  
- Pressures, ..

Control of **Product**:  
- Geometry  
- and  
- Properties

Desired Product  

CONTROLLER  

EQUIPMENT  

MATERIAL  

Product

Equipment loop  

Material loop  

Process output loop
Example: Machine and Process Control in a Microfluidics Manufacturing Cell
Sensing and Control

• Embossing Equipment
  – Temperature Feedback Control
    • Reduce Forming Variability
  – Force Feedback Control
    • Ditto
  – Displacement Monitoring
    • Detect Material or Machine Changes

• Channel Geometry
  – Quality of Forming

• Product Function
  – Flow Test
Sensing and Control

• Control?
  – “Standard” SPC
Sensing and Control: Material Properties

- Material Variation Compensation

**FIGURE 4. EXPERIMENTAL DEVICES WITH LOW DEGREE OF OVERFORMING (LEFT) AND HIGH DEGREE OF OVERFORMING (RIGHT).**

**Thickness Variations**

**Property Variations (T_g)**

Graph showing change in measured area vs. measured bell deformation, um. A quadratic fit is also shown.

Graph showing stiffness vs. heater temperature, °C. An inflection point is indicated.
Sensing and Control and “Moore’s Law”

• Product Performance – Characteristic Features
  – Variation or Uncertainty if Ultimate Limit

• Natural Variation vs. Controlled Variation
  – SPC vs. Output Feedback
  – No Adjustment vs. Continuous Adjustment
Application to CVD Thickness Control

Run to run control in tungsten chemical vapor deposition using H2/WF₆ at low pressures. Sreenivasan et. al. 2001

“alter the process time in order to maintain constant HF sensing signal”
Application To Emerging Technologies: Soft Lithography

5 Micron Silver ink Lines Printed on PMMA
CONTACT
MEASUREMENT AND CONTROL
Real-Time Output Pattern Sensing and Control
Contact Feedback Control

Open Loop: Constant Position Reference

Closed Loop: Camera to Position Reference

Petzelka & Hardt, ASPE 2011.

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Enabling Entirely New Methods: Continuous Pharmaceutical Production

Active Pharmaceutical Ingredient (API)

Drug Product (DP), tableting

Chemical intermediate → API

Multiple, disconnected batch steps

Multiple, disconnected batch steps

http://continuospharma.com/technology/
Enabling Entirely New Methods: Continuous Pharmaceutical Production

Continuous In-Process Measurement and Control Vs. “Batch Assays”

Chemical intermediates (prior to API)

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http://continuuspharma.com/technology/
Process Control in the Factory

• System Control
  – Multi-Process Feedback
  – Machine Health
    • MTBF, MTRR
• Parts Tracking
  – Knowing Where and How Many of What
• Assembly Completion
  – Knowing Everything is Complete and When
• Shipping
  – Knowing Everything is “In the Crate”
Example: Semiconductor Equipment Manufacturing

RFID in Shipping

Save 10 hrs out of 120-140 hrs

Air Shower

120-140 hrs

Shipping Area

• Module teardown with all wrapping works
• Check all parts present and final inspection
• Maintain count of extra parts
• Remaining tasks

• Double Wrapping
• General Crating
• Re-crating of WH parts
• Manually generated packing list
• Manually part count
Example: Semiconductor Equipment Manufacturing

RFID on Finished Product

- Significantly reduce part checking complexity and time
- Efficient missing parts tracking and pulling
- Track the parts at customer site

Technical Issues

- Metal interference is a big problem
- Reader/Antenna Access

- Antenna
- Tags on all Sub-assemblies
- Reader
Internal Supply Chain Tracking

Warehouse

Supplier → Data Entry → Inspection

Sorting → Shelving → Shipping Area

• Parts in

• Bins
Key Technology: RFID Systems

- **ID**
  - Electronic product code
  - Read-write extra memory/sensory data

- **Anti-collision**
  - One reader can read many tags

- **Reader coordination**
  - Make sure readers don’t interfere with each other

- **Middleware**
  - Collect all the data and make sense of it
Process Control Beyond the Factory:

• Supplier Networks Example: Toyota
  – Adoption of Process Control Methods Became key to Suppliers
  – Created a De facto Standard
  – Propagated Best Practices

• Future – Sensing and Control of Component History
  – Service
  – Warrantee
  – Recycling
Process Control in the Supply Chain

• Tracking of Product
  – Location
  – State
  – History

• Real-Time Warehouse Knowledge
  – Instant Inventory Status
  – Enables Novel Methods
    • Kiva Systems Dynamic Inventory Placement
Example: Supply Chain Problems

RFID enables:
- Real-time detection of errors
- Real-time correction
- Run-to-run improvement

i.e., tactical, operational, strategic enhancement.

Errors making plans less effective
The road to chaos is lined with good(s) intentions.

Manufacturing plant  Manufacturer’s DC  Retailer’s DC  Retailer

AGGREGATION  TRANSFER  SORTING  TRANSFER  SORTING  TRANSFER

CONTAINER  PALLET  CASE  SLEEVE  SINGLES

Too much inventory  Errors Shrinkage Wasted effort  Mis-shipments Shrinkage  Errors Inefficiencies Shrinkage

Don’t ask wasted actions PI resets

Holes Extras
The New Enablers

• Low Cost Self-Powered Sensing
  – On material as well as processes
  – In finished goods for tracking

• Simple, ubiquitous Communication
  – Wireless open-standard networks
  – Piggy-back on the “Internet of Thing” Movement

• The Impact of “The Internet of Things”
A Key Element: The New Connectivity
Production in the Innovation Economy (PIE)
A MIT study on the current state and future of innovation and manufacturing in the U.S.
• The Linkage Between Manufacturing and Innovation
• The Notion of an Industrial Commons
• The Rise of “Innovation Corridors”

• Co-Location Does Matter
• The Rise (again) of Cottage Industries
  – Enabled by the Ubiquitous Sensing, Control and Communication
  – Enabled by Self-Regulating Machines
  – Enabled by Well-Control Supply Chains

• The Need for Highly Skilled Workforce
  – Near Centers of Education
Conclusions

• AMP Got it Right!
• Sensing is Vital to Modern, Innovative (Advanced) Manufacturing
• Sensing and Control is a Key Enabler for Emerging Technologies
• Implications for the Entire Value Chain
• Benefits from the “Interconnected World”