2.830J / 6.780J / ESD.63J Control of Manufacturing Processes (SMA 6303)
Spring 2008

Control of Manufacturing Processes

Subject 2.830/6.780/ESD.63

Spring 2008

Lecture #1

Introduction

February 5, 2008

Background

- Pre-requisites
- Your Background and Interests
- Relevant Experience
- Course Schedule

Expectations

- Assignments ~ Weekly
- 2 Quizzes in Class
- Group Project
  - End of term presentation
  - Report

Syllabus Details

- **Lecturers**
  - **Duane Boning**
  - **David Hardt**
- **Course Secretary: Sharlene Blake**

Syllabus Details

- **Prerequisites**: One of the following :
  - 2.008 or 2.810 Manufacturing
  - 2.751J or 6.152J or 6.041 or 15.064J
- **Required Texts**:
  - Montgomery, D.C., *Introduction to Statistical Quality Control*, 5th Ed. Wiley, 2005
  - May and Spanos, *Fundamentals of Semiconductor Manufacturing and Process Control,* John Wiley, 2006.
- **Grading**:
  - Problem sets 40%
  - Quizzes 40%
  - Team Projects 20%
- **Assignments**: All except project are to be individual efforts
- **Final exam:** No final exam
- **Course URL**: (Registration and Certificate Required)

Team Projects

- Topics:
  - Process Diagnosis
  - Process Improvement
  - Process Optimization / Robustness
  - Advanced Applications

- Expectations
  - Background research on process and problem
  - Use of existing data or generation of new data
  - Oral presentation of results
  - Project report from group

Main Topics

- Physical Origins of Variation
  - Process Sensitivities
- Statistical Models and Interpretation
  - Process as a Random Variable(s)
  - Diagnosis of Problems
- Effects Models and Designed Experiments
  - Input - Output Empirical Models
- Process Optimization (Robustness)
  - Ideal Operating Points

Manufacturing Process Control

- Process Goals
  - Cost
  - Quality
  - Rate
  - Flexibility

Focus

- Unit Operations
- **(1) Maximizing Quality**
  - Conformance to Specifications
- (2) Improving Throughput
- (3) Improving Flexibility
- (4) Reducing Cost

Typical Process Control Problems

- Minimum feature size on a semiconductor chip has too much variability
- DNA diagnostic chip has uneven flow channels
- Toys never fit when assembled at home!
- Next generation high density electrical connector cannot be made reliably

Typical Process Control Problems

- Airframe skin needs trimming and bending to fit frame
- Web thickness of a machined panel is non-uniform
- Plastic throttle bodies for fuel injection are out of round
- Submarine hull welds need constant rework in production

Other Related Problems – Cost, Rate and Flexibility:

- 100% inspection with high scrap rates
  - low throughput
  - high costs

- 100% inspection with frequent rework
  - low throughput
  - high costs

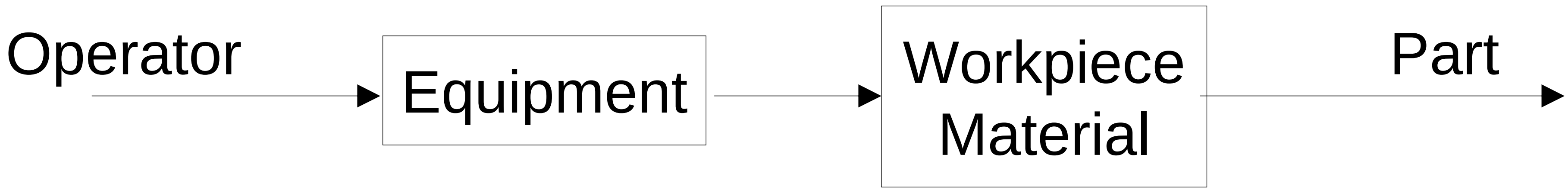
- High variability at changeover
  - Reluctance to changeover
  - low flexibility

Manufacturing Processes

- How are they defined?
- How do they do their thing?
- How can they be categorized?

- **Why don’t they always get it right?**

The Process Components



- Etch bath
- Injection Molder
- Lathe
- Draw Press
- ...

- Coated Silicon
- Plastic Pellets
- Bar stock
- Sheet Metal
- ...

- IC chip
- Connector Body
- Shaft
- Hood
- ...

Process Definition

A Manufacturing Process is a *Change* in the Workpiece *Material*

- A change in geometry
- A change in constitutive properties

Conceptual Semiconductor Process Model

Image removed due to copyright restrictions. Please see Fig. 1 in Boning, D. S., et al. “A General Semiconductor Process Modeling Framework.” *IEEE Transactions on Semiconductor Manufacturing* 5 (November 1992): 266-280.

Boning et al., *c.* 1990

Simplified Conceptual Semiconductor Process Model

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Example: Oxidation

Wafer states

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Example: Oxidation

Treatment (wafer environment)

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Oxidation Models

$$x_{ox} = \frac{A}{2}\left\{\left[1 + \frac{(t+\tau)4B}{A^2}\right]^{1/2} - 1\right\}$$

$$\tau = \frac{x_i^2 + Ax_i}{B}$$

Analytic: Deal-Grove

Empirical: Change in wafer state

Empirical: Equipment model for mean and std. dev. of oxide thickness

(Semiconductor) Manufacturing Process Control

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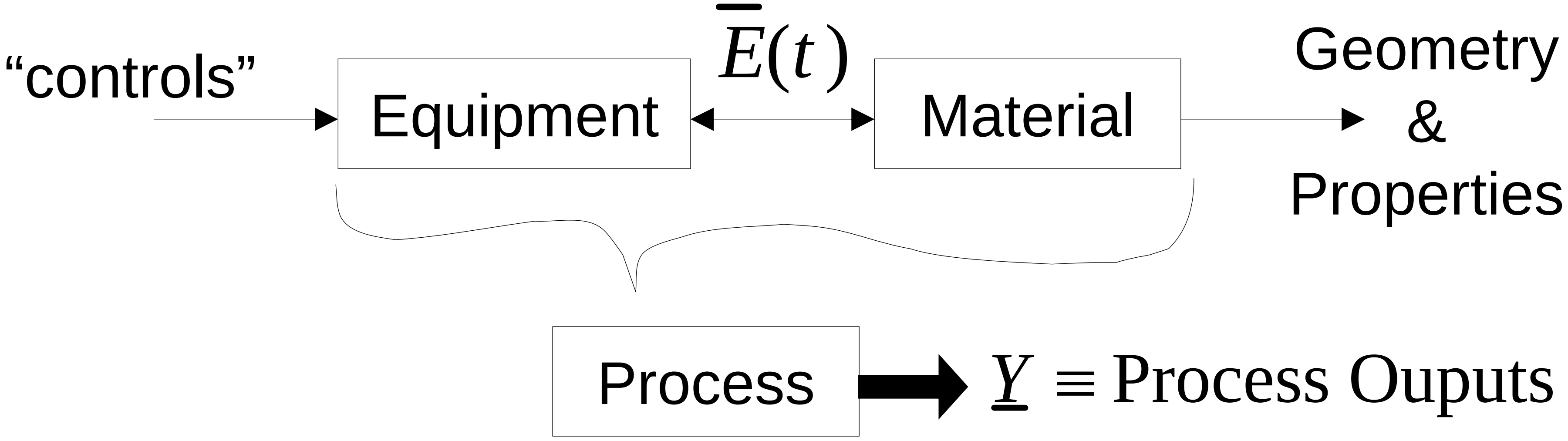
Process Model for Control



$$\underline{Y} = \Phi(\underline{\alpha})$$

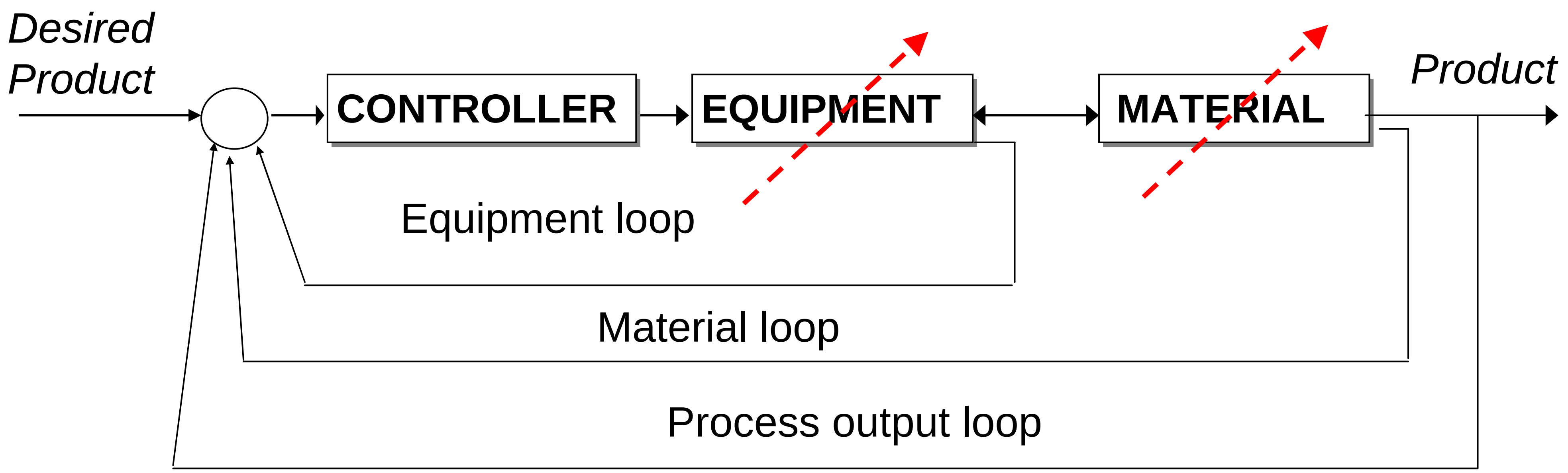
$$\underline{\alpha} \equiv \text{process } \mathit{parameters}$$

What are the α's?

Hardt, *c.* 1995

Manufacturing

The General Process Control Problem



Control of **Equipment**:

Forces,

Velocities

Temperatures, , ..

Control of **Material**:

Strains

Stresses

Temperatures,

Pressures, ..

Control of **Product**:

Geometry

and

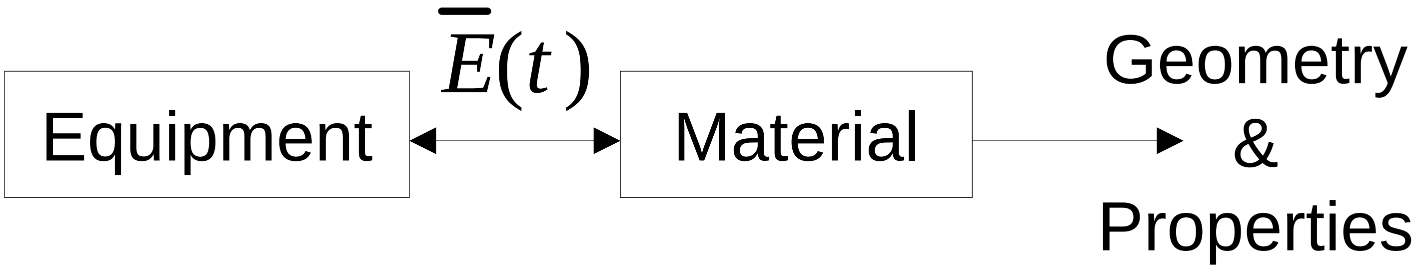
Properties

Process Control Hierarchy

- **Reduce Disturbances**
  - Good Housekeeping (Ops Management)
  - Standard Operations (SOP's)
  - **Statistical Analysis and Identification of Sources (SPC; 2.830J)**
  - **Feedback Control of Machines (Automation and Control; 2.168)**
- Reduce Sensitivity (Process Optimization or Robustness)
  - **Measure Sensitivities via Designed Experiments (2.830J)**
  - Adjust "free" parameters to minimize
- Measure output and manipulate inputs
  - **Feedback control of Output(s) (2.830J)**

Back to the Process: What Causes the Output Change?

- A Directed Energy Exchange with the Equipment



$$\bar{E}(t) \rightarrow \left\{ \begin{array}{l} mechanical \\ electrical \\ thermal \\ chemical \end{array} \right\}$$

Modes of Geometry Change?

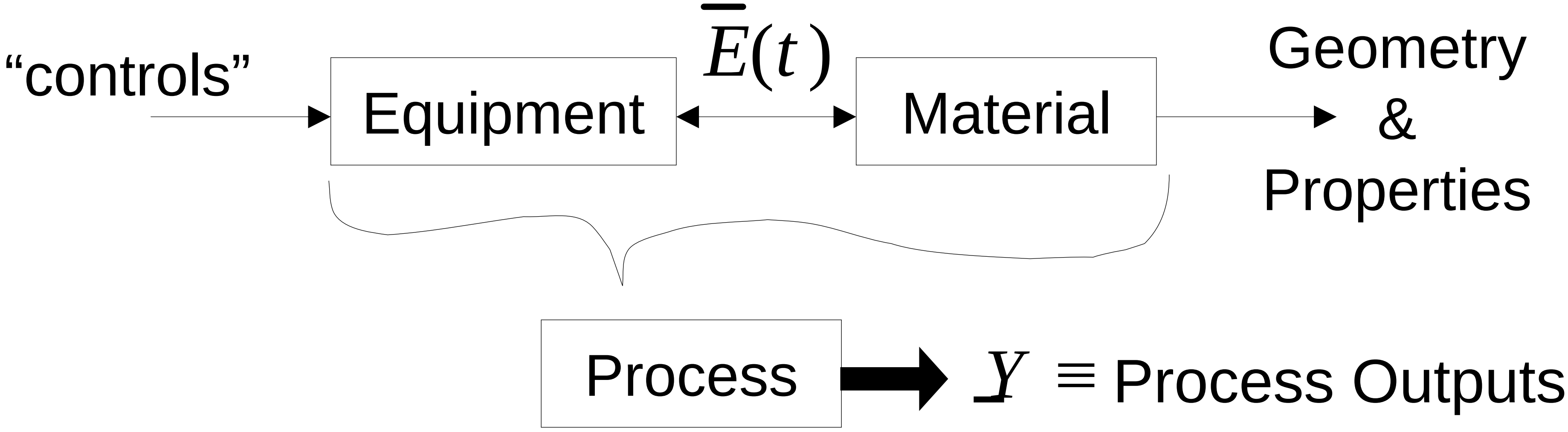
- **Removal** of Material
- Plastic **Deformation** of Material
- **Addition** of Material
- **Formation** of Material from a Gas or Liquid

- Any others???

What Causes *Variation* in the Process Output?

- Material Variations
  - Properties, Initial Geometry
- Equipment Variations
  - Non-repeatable, long term wear, deflections
- Operator Variations
  - Inconsistent control, excessive “tweaking”
- “Environment” Variations
  - Temperature and Handling inconsistencies

Process Model for Control



$$\underline{Y} = \Phi(\underline{\alpha})$$

$$\underline{\alpha} \equiv \text{process } \mathit{parameters}$$

What are the α's?

What *are* the *<u>Process Parameters</u>*?

- Equipment Energy “States”
- Equipment Constitutive “Properties”

- Material Energy “States”
- Material Constitutive ”Properties”

Energy States

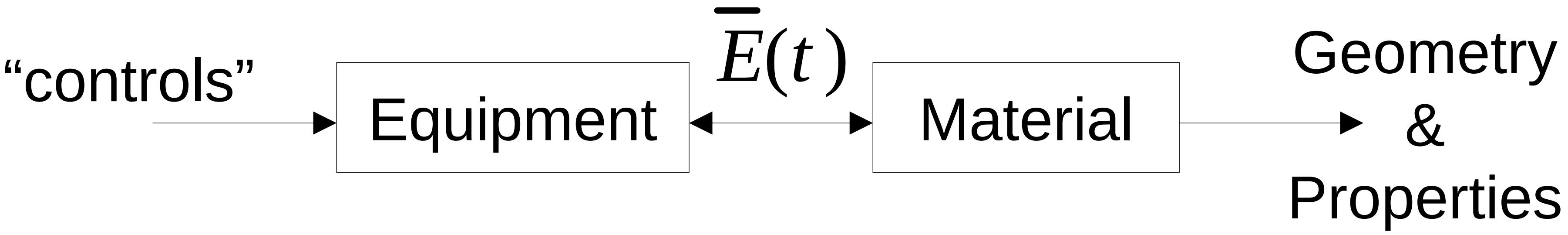
<u>Energy Domain</u>	<u>Energy or Power Variables</u>
Mechanical	*F, v* ; *P, Q or F, d* ; σ, ε
Electrical	*V,I*
Thermal	*T, ds/dt* (*or dq/dt*)
Chemical	chemical potential, rate

Properties

- *Extensive*: GEOMETRY
- *Intensive*: Constitutive Properties
  - Modulus of Elasticity, damping, mass
  - Plastic Flow Properties
  - Viscosity
  - Resistance, Inductance, Capacitance
  - Chemical Reactivity
  - Heat Transfer Coefficient

- Which has the highest precision?

A Model for Process Variations



- Recall: $\underline{Y} = \Phi(\underline{\alpha})$

- One or more α's "qualify" as inputs : $\underline{u}$

$$\underline{Y} = \Phi(\underline{\alpha}, \underline{u}); \qquad \underline{u} = \text{vector of inputs}$$

- The first order variation ΔY gives the "Variation Equation"

The Variation Equation

$$\Delta Y = \frac{\partial Y}{\partial \alpha} \Delta \alpha + \frac{\partial Y}{\partial u} \Delta u$$

Disturbance Sensitivity

Disturbances

Control Sensitivity or "Gain"

Control Inputs

Primary Process Control Goal: Minimize ΔY

How do we make $\Delta Y \rightarrow 0$?

$$\Delta Y = \frac{\partial Y}{\partial \alpha}\Delta\alpha + \frac{\partial Y}{\partial u}\Delta u$$

- hold *u* fixed ($\Delta u = 0$)
  - operator training (SOP's)
  - good steady-state machine physics
- minimize disturbances

$\Delta\alpha \rightarrow \Delta\alpha_{min}$

This is the goal of Statistical Process Control (SPC)

Manufacturing

OR

$$\Delta Y = \frac{\partial Y}{\partial \alpha}\Delta\alpha + \frac{\partial Y}{\partial u}\Delta u \qquad \Delta Y \rightarrow 0$$

- hold u fixed ($\Delta \underline{u} = 0$)
- minimize the term: $\frac{\partial Y}{\partial \alpha}$ the disturbance sensitivity

This is the goal of Process Optimization

- Assuming $\frac{\partial Y}{\partial \alpha} = \Phi(\underline{\alpha})$ $\underline{\alpha}$ = operating point

OR

$$\Delta Y = \frac{\partial Y}{\partial \alpha}\Delta\alpha \quad + \frac{\partial Y}{\partial u}\Delta u \qquad\qquad \Delta Y \rightarrow 0$$

- manipulate $\Delta \underline{u}$ *by measuring ΔY such that*

$$\Delta u \frac{\partial Y}{\partial u} = -\frac{\partial Y}{\partial \alpha}\Delta\alpha$$

This is the goal of Process Feedback Control

- Compensating for (not eliminating) disturbances

Statistical Process Control

$$\Delta Y = \frac{\partial Y}{\partial \alpha}\Delta\alpha \quad + \frac{\partial Y}{\partial u}\Delta u$$

Detect
and
Minimize

Process Optimization

$$\Delta Y = \frac{\partial Y}{\partial \alpha}\Delta\alpha + \frac{\partial Y}{\partial u}\Delta u$$

Empirically
Minimize

Output Feedback Control

$$\Delta Y = \frac{\partial Y}{\partial \alpha}\Delta\alpha + \frac{\partial Y}{\partial u}\Delta u$$

$$\frac{\partial Y}{\partial u}\Delta u = -\frac{\partial Y}{\partial \alpha}\Delta\alpha$$

Manipulate Actively Such That

Compensate for Disturbances

Process Control Hierarchy

- Reduce Disturbances
  - Good Housekeeping
  - Standard Operations (SOP's)
  - **Statistical Analysis and Identification of Sources (SPC)**
  - **Feedback Control of Machines**
- Reduce Sensitivity (increase "Robustness")
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