Manufacturing Processes and Process Control

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February , 1996

The following paper outlines a basic modeling paradigm for manufacturing process control. Once the model is defined, three distinctly different modes of process control are described based on this model The model then leads to a control taxonomy for manufacturing processes.

Model Definition

All manufacturing processes have but two *outputs*:

• Geometry (macroscopic shape of the product)

• Properties (all intrinsic material properties)

These two outputs completely define the performance of the product, and the design specifications that it must meet.

All processes also involve the transformation of **material** from an initial geometry and set of properties to the final outputs. This transformation is accomplished through the application (or removal) of energy, distributed about the surface or volume of the material. The source of this "directed energy" is the manufacturing machine or equipment. Thus, we can first define a manufacturing process as the interaction of equipment with a material to transform the material to the desired outputs geometry and properties. This model is shown in block diagram form in Fig 1.

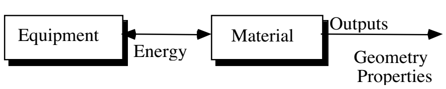


Fig. 1 The Relationship of Equipment and Material in a Manufacturing Process

Since all transformations are driven by and governed by the equipment, the only control over the process (other than changing the material itself) is through the equipment. Thus, the control inputs to the process are those equipment inputs that modulate the intensity and distribution of the energy input to the material. In other words, during the operation of the process, the only accessible means of controlled change is the equipment inputs. This leads to the process model shown in Fig. 2

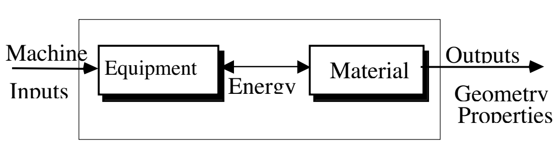


Fig. 2 Process Model with Equipment Inputs Shown

To help define internal variables in the process as well as the inputs and outputs, the basic output causality of the process model is shown in Fig. 3 using a simple functional relationship between the process output vector $\underline{Y}$ and the parameters of the process $\underline{\alpha}$.

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

The equipment inputs $\underline{u}$ are separated as a subset of the parameters that are accessible, certain and "manipulable" in a "reasonable" time frame relative to the basic process execution time.

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

The vector α can be further broken down into two categories:

- Material Parameters
- Equipment Parameters

Within both equipment and material parameters, we are interested in the thermodynamic state and the constitutive properties of each. For example, the equipment states will be the power pairs: force-velocity, pressure-flow, temperature- entropy (or heat flow) voltage-current, and chemical potential-extent of reaction. Material states can be the same quantities within the material. By contrast, the equipment properties govern how and when the energy is applied. Thus, the geometric, mechanical, thermal and electrical properties of the equipment determine its constitutive properties. Constitutive properties for the material are the well-known quantities such as stiffness, yield point, melting point, viscosity, etc.

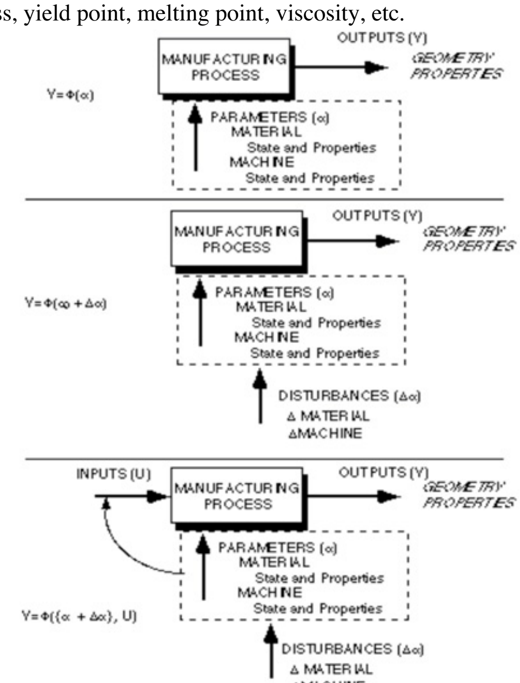


Fig. 3 Development of A Process Model for Control $\underline{Y}$ = process outputs α = process parameters Φ= the process transformation function. The parameter vector α is progressively broken down into disturbances ($\Delta\underline{\alpha}$) and inputs ($\underline{u}$)

In general, the states of the equipment and material change over the course of the process as energy is applied, whereas the constitutive properties tend to remain unchanged. However, the energy focused on the material often causes significant changes in the constitutive properties. Indeed the process outputs as defined above can be thought of as the **terminal** mechanical states and constitutive properties for the material.

Modes of Process Control

There are several ways in which processes are controlled, ranging from off-line sensitivity reduction to real-time output control. In all cases, the objective is to minimize the effect of disturbances (i.e. $\Delta\underline{\alpha}$) on the output $\underline{Y}$. This basic objective is captured by the first order variation equation:

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

where:

$\Delta\underline{Y}$ = variation of the output

$\frac{\partial Y}{\partial \alpha}$ = disturbance sensitivity of the process

$\Delta\underline{\alpha}$ = parameter disturbances

$\frac{\partial Y}{\partial u}$ = input-output sensitivity or "gain"

$\Delta\underline{u}$ = equipment input changes

To minimize the basic variation of Y we can:

• design and operate the process to have low disturbance sensitivities (minimize $\partial Y/\partial\alpha$). This is the goal of **process optimization**.

• design or control the equipment to minimize parameter variations $\Delta\underline{\alpha}$ This is the goal of **S**tatistical **P**rocess **C**ontrol (SPC)

• counteract $\Delta\underline{\alpha}$ by appropriate changes in $\Delta\underline{u}$, most typically through the use of **feedback control** to minimize $\Delta\underline{Y}$ over an appropriate frequency range

Sensitivity and Parameter Optimization

One means of characterizing the properties of a process is to quantify the effect of variations in the parameters on the outputs. This "generalized sensitivity function" takes the matrix form:

$$\frac{\partial Y}{\partial \alpha}$$

If such *sensitivity functions* are known, the process can then be tuned or "optimized" so as to minimize these functions. This control method is shown schematically in Fig. 4

In this control method the objective is to select nominal values of parameters α_O such that the sensitivity of the output to disturbances

$$\frac{\partial Y}{\partial \alpha}$$

is minimized. (Note that no inherent feedback loop exist here; thus changes in $\Delta\underline{\alpha}$ will not be directly compensated for.)

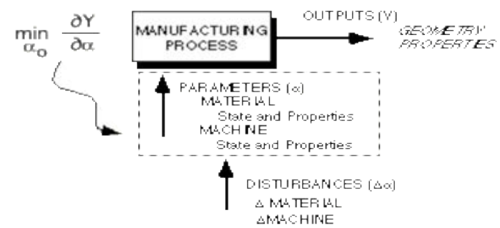


Fig. 4 Optimization of α_O to minimize the effect of $\Delta\alpha$

Statistical Process Control

SPC is actually a process diagnosis tool that tries to determine if process disturbances ($\Delta\alpha$) that are non-random in nature exist. This is done by examining the statistics of output data sampled from the process. If such disturbances are found, SPC provides no prescription for action, but implies that the disturbance should be eliminated. This is equivalent to detecting and eliminating $\Delta\underline{\alpha}$ (the disturbances) in the above variation equation. (This obviates taking any control action via $\Delta\underline{u}$.)

State Control using Feedback Systems

Since it is parameter variations that are responsible for variations in the process output, it is advantageous to try to reduce this variation. A common and very powerful method for reducing uncertainty is feedback systems, based on direct measurement of the equipment or material states. Examples of this include equipment force, velocity, temperature, pressure, or flow control. It may also involve control of material temperatures, pressures or displacements, for example. This method is shown in Fig.5

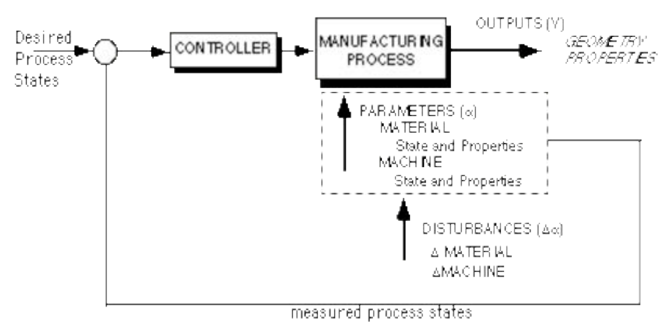


Fig. 5 Feedback Control of Process States.

There is an important distinction to be made between equipment state and material state control. In the former we have a much closer coupling between the inputs (equipment inputs) and the controlled variable (an equipment state). When the control is applied to the material state, the equipment and all its static and dynamic properties are included in the control loop as well as the often uncertain energy interaction "port"

In this method, we place certain parameters (a subset of the material states) α_e of the system under feedback control to reduce their variation or to render their values more certain. Thus, the effect of parameter variations on the outputs:

$$\frac{\partial Y}{\partial \alpha_e} \Delta\alpha_e$$

is reduced by reducing $\Delta\alpha_e$. Note that the outputs of the process and the disturbance effect on these are still outside the control loop.

Process Output Feedback Control

Ultimately the only means of insuring proper output target values and minimizing variation is to use feedback control directly on the outputs. As shown in Fig. 6, this strategy automatically encompasses ***all*** influences on the processes, provided a true output measurement is available. In practice this is seldom the case and the measurement process itself can add time delays and errors to the process.

(Note that we have added the measurement process as a separate problem, and indeed this problem can dominate in output control problems.)

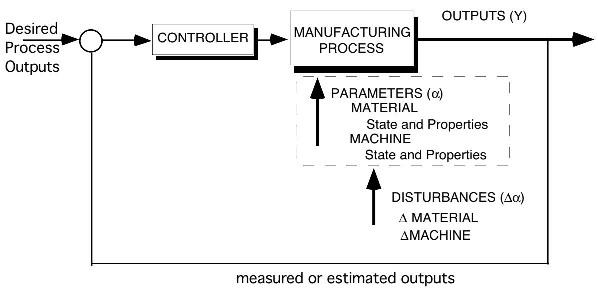


Fig. 6 Direct Feedback Control of Process Outputs

Finally, it is clear that many specific factors in the process physics and processing equipment design affect the ability to implement each of these types of control. The problem is discussed in detail in Hardt [1991], but the following helps to overlay the above framework on the universe of all manufacturing processes.

A Taxonomy for Control of Manufacturing Processes

The objective of process control is to force the process outputs of ***geometry*** and ***properties*** to match certain target values, and to create a "responsive" process. Ideally we would simply measure these outputs and adjust the appropriate controls, but most processes require a further breakdown of these objectives into control "sub problems". To help define these sub problems, it is first necessary to classify manufacturing processes in a manner that highlights the dominant control issues.

For example, both machining and closed-die forging have clear geometry and property outputs, but what determines these outputs for each process is quite different. It is this difference that makes machining an easy process to control in real-time and one that can respond quickly to command or target changes, but also one with a rather slow production rate. On the other hand, the geometry output of closed-die forging is nearly impossible to change in-process since complete tooling redevelopment is required each time a new target shape is needed. However, forging is often an order of magnitude faster in production rate than machining for parts of similar shape complexity.[1]

Why are these processes so vastly different in our control framework; one easily controlled and made responsive, yet slow, while the other is total unresponsive within a part cycle framework, yet very fast? The differences are many, and in fact the only similarity is that each uses mechanical energy on metals. For starters, machining induces shape change by removing material. Forging does so by deforming a fixed mass of material. Machining uses part -independent tooling that applies the transformation energy to a local region, creating the shape by moving the tool along a specified trajectory. Forging uses a part specific, "shaped tool" that creates the part in a single unidirectional stroke of the forging press, applying mechanical energy in a highly distributed fashion.

This simple example suggests at least one means of classifying processes for control; one that begins with the basic physical mechanisms of shape change, and then considers whether the change occurs locally or globally in time. Finally, to determine the physical processes that must be analyzed, modeled, measured and manipulated, delineating the dominant energy domain of the material transformation process will be necessary.

Process Classification for Control

Based on this discussion, a rudimentary hierarchical system of classification is suggested and is illustrated in Fig. 7

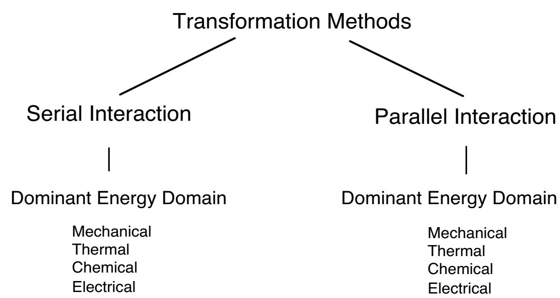


Fig. 7 Hierarchy of Process Classification for Control

At the head of this hierarchy is the transformation process or the actual mechanism of shape change. Such methods include:

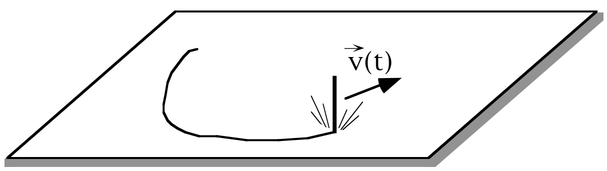
- Material Removal
- Material Addition
- Plastic Deformation
- Solidification

In each case a workpiece material is altered to create the desired shape, and within each category, all material types can be included, and different energy sources can be used. In addition, the transformation energy can be either applied locally and moved in a serial manner to create or follow the part contour, or applied everywhere on the part in parallel. It is clear that the details of the physical phenomena involved will depend upon the material type and

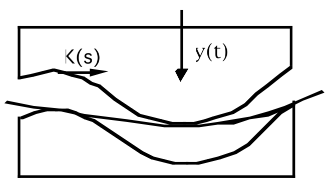
[1] One extreme example of this is the production of high performance landing gear for commercial aircraft. The part starts as an isothermal forging, which might take a few hours to complete. However, once finished the part must be machined, to refine the shape and improve dimensional accuracy, but this machining can take over 200 hours!

the energy source used for the transformation.   This distinction is shown schematically in Fig. 8

For example, a metal can be cut by imposing large local shear forces, causing the material to separate at the tool point. However, we can also cut this material by moving a concentrated heat source along the desired cut line. This heat can in turn come from a gas torch, a plasma arc or a laser beam. Concentrated shearing is also used to cut large parts from sheet, but rather than doing so at a point, or in a serial fashion, matched contoured cutting tools are used to cut (or "stamp") all portions of the part in parallel. While all of these processes are clearly "removal" processes, they differ significantly in the other areas of the classification hierarchy, and these differences will directly affect upon our ability to control them.



a) Serial Process (e.g. laser cutting)



b)Parallel Process (e.g. sheet stamping)

Fig. 8 Classification of Manufacturing Processes   Note that for the serial process geometry is determined by the time varying velocity vector while for the parallel process the curvature distribution K(s) is the primary determinant of geometry

Finally, the dominant energy used in the transformation has significant impact on the speed and accuracy of the process. In general mechanical and electrical processes are extremely fast and these energy forms can be applied to very small or very large areas, whereas thermal and chemical energy process are diffusive by nature and tend to have long time constants. Processes dominated by these domains are typically rate limited by heat transfer or reaction rate limits, and even if energy is locally applied it quickly diffuses into the material (e.g. welding).

As a first attempt at applying such a classification scheme, many of the common processes in use today are listed in Table 1 according to this scheme.

Serial and Parallel Processes

After categorization by transformation method, the serial/parallel distinction is perhaps the most important from the point of view of control since it will have the greatest impact on the controllability and time frame of control. Serial processes are those that modify geometry and properties by moving a local process along a prescribed trajectory, making changes in sequence. These processes include most machining, laser processing, welding, rolling and many assembly processes. The set of control problems in serial processes always includes an equipment displacement or trajectory control problem. Also, most robotic processes are by definition serial processes, and, although tooling is present, is it usually not specific to any one part.

Parallel processes are those that affect large regions of a workpiece simultaneously. These processes include all that use shaped tooling (forming, forging, casting, molding, etching, ECM or EDM) and additive processes such as powder based, spray or plating processes. In most cases any "trajectory" that is involved is a simple single axis movement and has little effect on part geometry. For parts with shaped tooling, the geometry is essentially completely determined by this tooling, and seldom can it be changed in-process. As a result, this type of process often has very long time constants for change.

In some cases there are boundary conditions such as global forces, temperatures and pressures that can change the relationship between the tooling shape and the final part shape, and while these can be changed rapidly, their effect is still global in nature.

As for control, serial processes typically are more controllable, because local changes do not affect the global part, and changes in time correspond to spatial changes over the extent of the part. Since all the "action" is easily located in the region of the local process, measurement is simplified, and models can be developed that are valid locally without as much concern about the global accuracy. With serial processes gross changes in geometry can be effected simply by changing the trajectory and the process in concert. Little or no fixed tooling is used (except to fixture the parts prior to processing)

Parallel processes are not well modeled by conventional feedback control methods, but some research has uncovered useful application of system theory to certain problems. In most cases, the only means of process control are statistical in nature and cannot exert significant control authority. Such processes are typically quite inflexible, since the time constant of change is very long compared to the part processing time

In most categories of material transformation methods, such as those listed in Table 1, there are both serial and parallel processes. As will be demonstrated in each of these categories, our ability to effect control will vary in direct relation to whether the process is serial or parallel.

One of the best examples of how process design can be used to improve control properties is the recently invented process of stereo lithography. (Kodama, 1981, Hull, 1986) This process (listed in Table 1 as a solidification/serial/thermal process) is in fact the serial version of more conventional polymer molding processes. By selectively solidifying the material, the need to a model is eliminated, and the outer shell of the part as it is produced becomes the mold. This eliminated fixed tooling, and converts the process control problem into one of primarily trajectory control, since the local polymerization process is well behaved and can operate well in an open-loop fashion. Other processes such as laser sintering (Deckard, 1989) and 3-D printing (Sachs et al., 1990) are examples of taking parallel process physics and converting it to a serial process.

Summary

This paper presents a simple model to help understand the universe of manufacturing processes in the context of their control. By defining the function of a process as geometry change of the workpiece, and delineating the role of the machine or equipment, the actual means of control for any process can be defined. This is addressed with the "Variation Equation" that illustrates the respective roles of three dominant process control methods: Statistical Process Control, Process Optimization and Feedback Control. Finally, the limits on control are expressed in a process taxonomy that categorizes processes according to how easily and rapidly the output can be changed by manipulating the equipment.

References

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4.Kodama, H., (1981), “Automatic Method for Fabricating a Three Dimensional Plastic Model with Photo-Hardening Polymer”, Rev. Sci. Instrum., 52,m no. 11, Nov.

5.Sachs, E., Cima, M., Cornie, J., Brancazio, D., and Curodeau, A., (1990), “Three Dimensional Printing: Ceramic Tooling and Parts Directly from a CAD Model”, Proc. National Conference on Rapid Prototyping, Dayton, June.

Table 1 Process Taxonomy for Control

Transformation	MATERIAL *REMOVAL*							
Control Mode	**SERIAL**				**PARALLEL**			
Energy Source	Mechanical	Thermal	Chemical	Electrical	Mechanical	Thermal	Chemical	Electrical
	Cutting *Grinding* *Broaching* *Polishing* *Water Jet*	*Laser Cutting* *"Flame" Cutting* *Plasma Cutting*	*ECM*	*EDM*	*Die Stamping*		*ECM* *Photo-lithography* *Chemical Milling*	*EDM*

Transformation	MATERIAL *ADDITION*							
Control Mode	**SERIAL**				**PARALLEL**			
Energy Source	Mechanical	Thermal	Chemical	Electrical	Mechanical	Thermal	Chemical	Electrical
	3D Printing *Ultrasonic* *Welding*	*Laser* *Sintering*	*Painting*	*E-Beam Welding* *Arc Welding* *Resistance Welding*	*HIP* *Inertia Bonding*	*Sintering*	*Diffusion Bonding*	

Transformation	MATERIAL *FORMATION*							
Control Mode	**SERIAL**				**PARALLEL**			
Energy Source	Mechanical	Thermal	Chemical	Electrical	Mechanical	Thermal	Chemical	Electrical
		Plasma Spray *DBM*	*Stereo-lithography*			*Casting* *Molding*	LPCVD *Plating*	

Transformation	MATERIAL DEFORMATION							
Control Mode	**SERIAL**				**PARALLEL**			
Energy Source	Mechanical	Thermal	Chemical	Electrical	Mechanical	Thermal	Chemical	Electrical
	Bending *Forging (open die)* *Rolling*	*Line Heating*			*Drawing* *Forging (closed-die)*			*Magneto-forming*

TABLE KEY	
Transformation	Method of Geometry Change
Control Mode	**Local or Global Change**
Energy Source	Primary Energy form used for Change