Modeling and Control of Manufacturing Processes: Getting More Involved

David E. Hardt
Laboratory for Manufacturing and Productivity,
Massachusetts Institute of Technology,
Cambridge, MA 02139

The discipline of control has had numerous yet sporadic contacts with the manufacturing world over the past few decades, almost always as an afterthought or addendum, and typically in the role of machine and not as process control. Much of this detachment comes from an absence of control techniques that can deal directly with the actual manufacturing process, i.e., a material transformation process that produces a desired object both in terms of specific geometry and internal properties. Instead, most efforts have focused on using existing methods on process independent problems, such as position control and trajectory following, or on straightforward process parameter control, thereby only indirectly influencing the actual process output. This paper presents the reasons behind and the means to eliminate this estrangement, using the author's own research as an example of a more direct approach to process modeling and control.

Introduction

I recall an early meeting I had with my Department Head, Prof. Herb Richardson, soon after joining the faculty at MIT in 1979. I was supposed to work in manufacturing, but my experience was mainly with system dynamics, control, and human motion. I remarked that manufacturing processes are so variable and poorly modeled that I didn't really know where to start. He replied (perhaps with some exasperation, although I truly don't recall) that such uncertainty was precisely why control was necessary, and, "*Oh, by the way*, I want you to head up a new Technical Panel on Manufacturing in the Dynamic Systems Division of ASME." I took his comments quite seriously (especially the second) and have since then been using the control perspective to view manufacturing processes as a continuing challenge to our paradigms in modeling, measurement, and control, and to repeatedly claim that control is not only appropriate but essential for the proper analysis of manufacturing.

As I early on observed, manufacturing processes present a vast array of machines and material transformation methods, and lists of such processes often have hundreds of entries. Yet common elements do exist, and these can in fact be found by taking a control perspective on the problem. All manufacturing processes involve a complex *geometry transformation* coupled with a *property transformation*, where by the intrinsic characteristics of the workpiece material are modified, either intentionally or unintentionally. Added to these generic objectives are the operational concerns of producing these transformations accurately and repeatedly, with the capability of changing the target geometries rapidly (in other words, quality and flexibility in production environment). From a process *operation* point of view, these statements translate into the process objectives:

- Minimize production variations for a given geometry and property target in the face of material and processing environment uncertainties (quality)
- Respond rapidly to demand changes (flexibility)
- Maximize productivity (rate)

Now compare these with classical feedback system objectives:

- Match output to input even when disturbances occur (disturbance rejection), and when plant model uncertainties exist (parameter insensitivity)
- High bandwidth response to new inputs (tracking)
- Maximize stable bandwidth

There is a clear one-to-one correspondence between process objectives and the objectives of a feedback system. The reason for this apparent match between control theory and manufacturing process analysis lies in the match between the goals of process operation and control systems. Both seek to produce an output from a commanded input, with minimum error, and both must deal with unexpected external disturbances (e.g., material property changes) or uncertainties in the process under control. It is further apparent that feedback control is *always* present in manufacturing, whether in the form of high bandwidth servos or in the response to a customer complaint about poor quality.

Yet most intersections of control with processes have not exploited this connection. Instead, they have concentrated on more removed electromechanical or thermal control problems associated with the machine as opposed to the material transformation process itself. This paper presents the general case for process control and gives some reasons for this lack of immersion in the process by dynamics and control researchers. Through the use of two specific research project results, ex-

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Contributed by the Dynamic Systems and Control Division for publication in the JOURNAL OF DYNAMIC SYSTEMS, MEASUREMENT, AND CONTROL. Manuscript received by the Dynamic Systems and Control Division February 4, 1993.

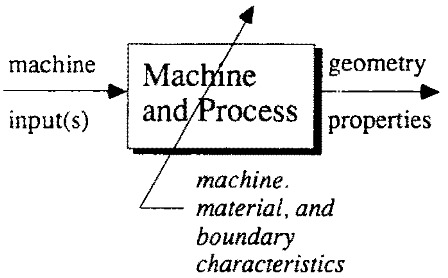

Fig. 1 Block diagram of a manufacturing process

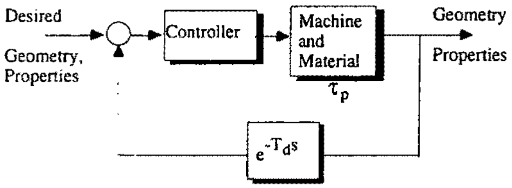

Fig. 2 Canonical process control block diagram

amples of how control can be more involved with the process are developed.

Manufacturing Processes

From a control perspective, a manufacturing process is easily modeled as an I/O function, as shown in Fig. 1. Notice here that this block includes both the actual material transformation process and the machine supplying and modulating the transformation power. The outputs from *any* manufacturing process are by definition the geometry and properties of the product. The input is that set of machine variables that have a clear and deterministic causal effect on the output, and the input-output relationship is parameterized by the characteristics of the workpiece material, the working environment or boundaries, and the basic characteristics of the machine in use. The *raison d'être* for process control is the rejection or elimination of disturbances that typically arise from the parameter variations, primary among these the uncertainty and variation of material properties. Uncertainties also arise from the inability to precisely model in sufficient detail the physics of most three-dimensional manufacturing processes.

From this process block, a generic manufacturing process control block diagram can be drawn, as in Fig. 2. The essential features of this diagram are the dominant time constant τ_p of the process, and the delay characteristics, T_d, of the feedback. The time constant represents either the process dynamics or the cycle time of the process for completion of a single product. The measurement delay is used to delineate various forms of process control. These are summarized in Table 1:

While there are much more detailed differences among these various approaches (see for example Box and Kramer (1990), who make a detailed comparison of statistical process control and feedback control), Table 1 illustrates that all processes are subject to some type of feedback control, either automatic or human-operated, and even "no-control" involves feedback in the form of customer complaints or warranty recalls.

The Control Problem

As stated at the outset, the goals of any process can be divided into three major categories: quality, flexibility, and rate. To the extent that control improves a process in each of these categories, the process becomes more attractive. In addition, it should be noted that only high bandwidth or real-time control methods can achieve all three of these objectives, since, for example, techniques such as statistical process control (see Montgomery, 1991) or process optimization (e.g., Taguchi, 1986) work only with a fixed process and intentionally do not seek to improve tracking (flexibility) or bandwidth (rate).

Table 1 Families of control methods based on decreasing bandwidth

	Control Method	Bandwidth
$T_d < \tau_p$	Real-time or in-process control	High
$T_d = \tau_p$	Iterative control	↓
$T_d \sim 10\text{–}100\ \tau_p$	Sampling and statistical process control	↓
$T_d \sim 10^3\ \tau_p$	Empirical modeling and process optimization	↓
$T_d \sim$ months	Warranty recall	Low

The remainder of this paper concentrates on the class of problems defined above as real-time or iterative, but even within this class some important distinctions must be made before proceeding. The most important distinction is between *process output control* and *process parameter control*.[1] In the former, the primary feedback for the control is the process output: The geometry and/or properties of the *product*. In the latter, the feedback is typically from a measurement made on some intermediate machine or material state (such as forces, displacements, or temperatures), none of which are the process output, but all of which help determine it, albeit indirectly.[2] In addition, the measured states may or may not reflect the interaction of the machine with the material. Thus, unless the control system is using a direct measurement or observation of the process outputs, it must be considered *process parameter* control. The implications of this distinction are obvious: the process under parameter control leaves the actual geometry generation process outside the loop, thus precluding complete disturbance rejection.

For example, in the process of simple metal cutting, the output is the new surface geometry of the part, and the input is the angular position of the leadscrews on the machine. The process parameters include the machine stiffness, straightness of the ways, the spindle dynamics, the tool geometry and stiffness, and the hardness of the workpiece, as well as the forces displacements and temperatures of the machine, workpiece, and tool. Direct output control would require that the new surface geometry be measured directed at the tool-material interface, and then use this feedback to control the position of the leadscrews. However, if instead we build a control system that carefully controls the position of the leadscrews and can track a prespecified trajectory,[3] the actual cutting process is outside the loop and control is exerted only on the parameter of leadscrew position. While output control clearly appears superior, it also requires modeling the cutting process in sufficient detail to insure a stable, consistently performing controller design. As a result, almost all examples of machine tool control are process parameter control, but since the machining processes tend to be well behaved and the output geometry is determined to first order by the trajectory of the cutting tool, this is not a severe drawback.

Contrast this with the process of injection molding. The key

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[1] In this discussion, *process parameters* refer to all variables that determine the process outputs, including dynamic states of the machine and the material, as well as the basic constitutive relationships for each.

[2] It is sometimes useful to think of the "customer" when considering process control; we can sell the output product geometry and properties, but no customer is interested in buying the temperature or displacement history of the process that produced it.

[3] This is in fact the definition of numerical control (NC).

process outputs here are the shape and density of the molded part. Typical control in injection molding involves closed-loop regulation of barrel temperatures, mold-cooling water temperatures, screw speed and position, and injector velocity (all of which are machine state variables). Clearly, all of these parameters affect the process outputs, but none are primary determinants of shape, which is in fact determined almost entirely by the shape of the mold in use.

Thus a clear difference exists between these two processes. In the first case, a single, easily controlled parameter, tool position, is directly related to the process geometry output, whereas, in the second case, the real-time control systems in use have a slight, diffuse effect on the part outputs.

Serial and Parallel Processes

This last observation leads to an important classification of the universe of manufacturing processes: *serial* and *parallel*. In serial processes the actual material geometry transformation occurs in a small region usually localized around a directed energy source, for example a milling cutter, a welding torch, or a water jet. By contrast, parallel processes involve simultaneous (i.e., highly coupled spatially) transformation in all regions of a workpiece in parallel. This includes processes such as plating, sheet stamping, forging, and the cooling phase of casting or molding. There is in fact a spectrum from purely serial to purely parallel, depending upon how localized the transformation is relative to the scale of the part. For example, steel or aluminum rolling mills are somewhere in between, since along the length of the material the process is clearly localized or serial, whereas across the width it is parallel.

This serial/parallel distinction is critical to understanding the feasibility of real-time control. This can be understood simply by considering the main source of geometry or shape information in these two classes of processes. In serial processes, the primary determinant of shape is the trajectory of the tool, as shown for example in Fig. 3(*a*). Since shape information contained in the trajectory is a temporal quantity, $\vec{v}(t)$, it can be instantaneously changed using well established motion control methods. Thus, the decades of work on servos, electromechanical drives, and position and velocity measurement can be brought to bear on this control problem. By contrast, the parallel process (see Fig. 3(*b*)) compresses all of the shape change into a single, rather short time interval, and typically uses a simple trajectory with a complex tool. Since the information about shape is contained in the curvature of the tool $K(s)$, it is not easily changed, and process control efforts here are typically limited to minimizing variations about a well defined target, usually by some type of parameter control. Thus we can expect and will indeed find that real-time control research in manufacturing over the past two decades is dominated by work in serial processes, and within those, by *machine* parameter control instead of output control problems.

Two Decades of Manufacturing Control Research in the JOURNAL OF DYNAMIC SYSTEMS, MEASUREMENT, AND CONTROL

As a measure of the involvement of control in manufacturing, I have reviewed the history of the ASME JOURNAL OF DYNAMIC SYSTEMS, MEASUREMENT, AND CONTROL through the lens of process control as defined above. From the period January 1971 to the present, there have been approximately 25 papers[4] clearly concerned with manufacturing processes, and the bulk of these have come in the past decade. Since over 1200 papers have been published over this period, this amounts to about 2 percent of the total publications in the JOURNAL. This does not appear to make manufacturing a mainstream concern of the dynamics and control community. In addition, a breakdown of the paper shows that they represent only a small corner of the universe of manufacturing processes.

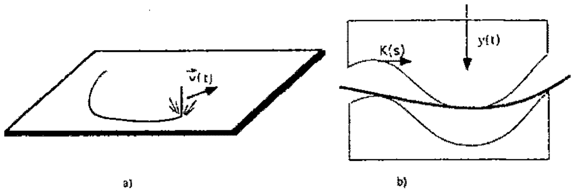

Fig. 3 Classification of manufacturing processes. (*a*) serial process (e.g., laser cutting); (*b*) parallel process (e.g., sheet stamping)

Of the 25 papers, all but one are concerned with control of serial processes, and most (15 or 60 percent) are concerned with one process: *machining*. This is not surprising, considering how ubiquitous machining operations are, but they do not represent 60 percent of the world's discrete part production! Also, in all cases of machining, the control is best categorized as parameter control, concentrating on tool position control (two papers), force measurement and control (six), regenerative chatter control (four), or optimal path planning (three). What is interesting about this summary is that it suggests that once the basic servo problem was solved for NC machining in the early 1950s (see Reintjes, 1991), little additional, fundamental work was needed on the primary control of this process, and work has instead concentrated on incremental improvement in rate limiting conditions, such as maximum feedrates to avoid tool breakage, excessive tool wear, or tool chatter.

The next largest category of process control papers is in the area of arc welding, although this amounts to only 6 papers. Again, welding is a serial process and lends itself easily to the application of conventional lumped parameter modeling and control methods. (Welding control will be considered in detail below as a case study in serial process control.) As of about 1980, welding had seen considerable application of simple feedback control to process parameters such as welding current, wire feed velocities, and arc voltage (via arc length manipulation). However, in contrast with machining, almost all of the welding research in the JOURNAL has dealt with process outputs, such as bead geometry or weld material properties.

A pair of papers on output control (i.e., curvature) in metal bending (Trottsman et al., 1982; Hardt et al., 1982) again illustrate the strong bias of control investigators for serial processes. In general, material deformation processes such as sheet stamping or forging would be categorized as parallel, since they are dominated by shaped tooling, and highly distributed stress-strain fields. However, there is a small class of processes, specifically roll bending, where the bending is localized and applied serially to the length of a workpiece. In so doing, the control action can be localized, and can act in real-time, provided an appropriate output estimation scheme is employed.

The one paper in the JOURNAL concerned with an unquestionably parallel processes is by Shankar and Paul (1982), and it develops by using a dynamic model of injection molding. The model considers lumped parameters only, which cannot capture the spatial aspects of this process, but it does look at parameters near the outputs, such as mold pressure and plastic temperature in the mold. Interestingly, the authors conclude that discrepancies between the model predictions and experimental results are caused by the inadequacy of the lumped model to account for distributed processes such as heat transfer and fluid flow that dominate this process.

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[4] These papers are listed in the bibliography at the end of this paper. Note the absence of papers on robotics, since they all have concentrated on control issues related to the manipulator itself, and not only the process being executed by the machine. Other journals, most particularly the ASME *Journal of Engineering for Industry*, have not been reviewed, since the objective here is to emphasize the efforts of the dynamics and control community.

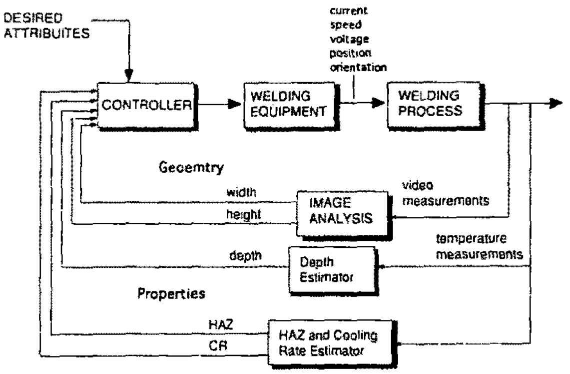

Fig. 4 A basic MIMO block diagram for welding output control

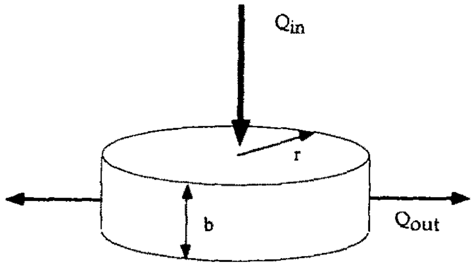

Fig. 5 Heat transfer model for GTAW. Q_{in} is the welding torch input and Q_{out} is the conduction to the weldment from the periphery of the pool.

When considering symposia sponsored by the Dynamics and Controls Division of the ASME, one finds a greater number yet similar variety of papers in evidence. Since 1983, the division has sponsored 10 symposia focused on manufacturing processes[5] through the Technical Panel on Manufacturing. Again the dominant themes are serial processes, parameter control, and machining.

I guess Herb Richardson had a good idea in setting up the panel, based on the success of the symposia, but by including the archival papers this rather cursory review indicates that the dynamics and control community within ASME has not really leapt into the process control arena, perhaps because of the nontraditional physical models that are required for real-time process control, and because a number of processes can be well controlled without directly involving the process physics. However, as the next two examples illustrate, there are real and exciting challenges in manufacturing process development that perhaps should be led by those in the dynamics and control community, but which require broadening our perspective as to what constitutes a feasible problem. These two areas, welding and forming, have been part of my research since that early meeting with Herb. The first was instigated by both Profs. Nam Suh and Hank Paynter at MIT, while the second owes its earliest thought to Prof. Nam Suh.

Case I: Output Control of a Serial Process—Welding

As mentioned above, welding is a serial process that appears amenable to conventional lumped parameter control methods. A basic view of the welding control problem is diagrammed in Fig. 4, where both geometry and property outputs are shown. In this case, the properties are indirectly controlled through the regulation of the thermal history of the process. Our work on this problem has been divided into process output measurement (e.g., Zachsenhouse and Hardt, 1983; Hardt and Katz, 1984; Bates and Hardt, 1985; Tam and Hardt, 1989; and Song and Hardt, 1990), process modeling for control (e.g., Hardt et al., 1985; Doumanidis and Hardt, 1989; and Hale and Hardt, 1990a), and control of outputs (e.g., Doumanidis and Hardt, 1991; Suzuki and Hardt, 1991; Hale and Hardt, 1990b; and Song and Hardt, 1992).

As an example of the use of control methods for welding, consider the modeling of the process for control. Welding is a complex, multi-energy domain process that involves phenomena as diverse as plasma physics, fluid flow in molten pools of indeterminate shape driven by convection, thermal gradients, surface tension gradients and plasma-pool interaction, three-dimensional heat conduction, and consumable wire heat and mass transfer. To construct an input-output model from this morass of factors appears daunting at best, yet all that is needed is a dynamic model relating accessible input quantities, such as welding current and travel speed, with outputs such as bead width, depth, or cooling rate.

In Hardt et al. (1985), the simplest of processes, gas tungsten arc welding (GTAW), was modeled using a lumped parameter heat transfer model, illustrated in Fig. 5. The intent was to relate input welding current to the output bead width for full penetration welds. This model was predicated on observed step response data relating the input current (I) and the output pool width (r) that appeared first-order, but which also indicated that the input-output relationship was nonstationary. The heat balance for the control volume encompassing the weld pool is given by[6]:

$$Q_{\text{in}} - Q_{\text{out}} = h_f \frac{dV}{dt} \tag{1}$$

where Q_{in} is the heat supplied by the torch, Q_{out} is the heat conducted to the weldment, V is the pool volume, and h_f is the heat of fusion for the material. When the geometry of the pool is used to determine the volume, V

$$V = 2\pi r^2 b \tag{2}$$

and the conduction equation for the periphery is developed, the system equation becomes:

$$K_1 r \frac{dr}{dt} + K_2 r = K_3 I \tag{3}$$

where I is the welding current and

$K_1 = 4\pi b\ h_f$

$K_2 = 2\pi k b \dfrac{d\theta}{dr};$

$\left(\dfrac{d\theta}{dr} = \text{radial temperature gradient at the interface}\right)$

$K_3 = \text{arc voltage} * \text{arc efficiency}$

This simple model makes it clear that although a simple first-order model can be used to capture the dynamics, the parameters K_1 and K_2 vary directly with the output r, the local thermal gradient $d\theta/dr$, and the thickness and thermal properties of the weldment. Most of these can and will change rapidly during welding, thus the process must be considered highly nonlinear in operation.

This nonlinear behavior was confirmed and expanded upon by Doumanidis and Hardt (1989), and Hale and Hardt (1990a). In the former, the desire was to relate the heat input from two separate sources to the heat affected zone width (HZ) and the centerline cooling rate (CR). Using a combination of simple analytical heat transfer modeling, nonlinear finite difference heat transfer modeling, and experimentation, a second-order transfer function matrix was developed relating input and out-

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[5] See the Bibliography for a listing of these symposium volumes.

[6] This assumes that the pool is isothermal and cylindrical in shape.

puts. The dominate time constants of this matrix were shown to be dependent upon the operating point of the process, but no specific functions were given for this variation.

Hale and Hardt (1990a) again developed a 2 × 2 transfer function matrix, but this time related output width and height to input current (or wire feedrate) and travel speed. The actual relationship was given by:

$$\left|\begin{array}{c} y_1(z) \\ \\ \\ y_2(z) \end{array}\right| = \left|\begin{array}{c:c} \dfrac{(b_{11}+b_{12}z^{-1})z^{-d_{11}}}{1+a_{11}z^{-1}+a_{12}z^{-2}} & \dfrac{(b_{13}+b_{14}z^{-1})z^{-d_{12}}}{1+a_{11}z^{-1}+a_{12}z^{-2}} \\ \hdashline \dfrac{(b_{21}+b_{22}z^{-1})z^{-d_{21}}}{1+a_{21}z^{-1}+a_{22}z^{-2}} & \dfrac{(b_{23}+b_{24}z^{-1})z^{-d_{22}}}{1+a_{21}z^{-1}+a_{22}z^{-2}} \end{array}\right| \left|\begin{array}{c} u_1(z) \\ \\ \\ u_2(z) \end{array}\right| \tag{4}$$

where u_1 and u_2 are the wire feedrate (current) and the inverse travel speed, respectively, and y_1 and y_2 are the bead width and height.

Notice here that each output pair has common dynamics and that each I/O pair has a different delay term associated with it. It was also found that the denominator terms a_{ij} varied directly with travel speed such that the natural frequency of the system *increased* with travel speed. In addition, the gain terms b_{11} and b_{13} were found to vary nearly linearly with the wirefeed rate. This model and its nonlinearities were confirmed later by Song (1992), in a series of identification experiments using a pseudo-random binary sequence input.

Clearly, therefore, the process of welding, when viewed as a lumped output system, has strong nonlinear behavior, but this behavior can be described with nonstationary linear models developed empirically, in a form suitable for on-line parameter identification.

Process Output Control. The above modeling strongly suggests the use of adaptive control to account for the continuously nonlinear behavior. Accordingly, an initial investigation of the full penetration GTAW width control was conducted by Suzuki et al. (1991). Here the control system was a single input-single output system using current I and width r. It was found that simple PI methods were totally inadequate for consistent width regulation owing to highly variable heat transfer and torch voltage behavior. In addition, step changes in the thickness of the material caused very poor transient response. By contrast, when a parameter adaptive scheme was applied (either parallel model reference control[7] or self-tuning control[8]), the transient performance of the process became very consistent, and severe parameter disturbances (e.g., thickness or velocity changes) were easily rejected.

This adaptive control approach was pursued by Doumanidis and Hardt (1991) for controlling the thermal outputs HZ and Cr, and by Song and Hardt (1992) for controlling the geometric outputs of width (W) and depth (D). In both cases, the one-step-ahead method of Goodwin and Sin (1984) was applied because of its applicability to MIMO systems. However, this approach led to excessive control effort, and some modifications were necessary. In the former case an external PI loop was placed around the entire system to smooth the input, but this limited the system bandwidth. For the latter problem, however, the use of control weighting factors prevented the controller from attempting zero error in a single step, and thus smoothed the response without a large bandwidth penalty (for example, see Fig. 6).

In both cases, the adaptive controllers were shown to be stable and adequate to account for the nonlinear behavior of the process.

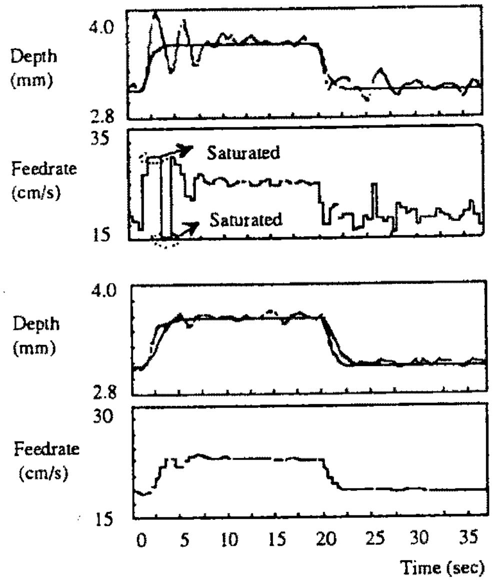

Fig. 6 Depth responses of OSA adaptive controller for (*a*) no control weight and (*b*) control weight = 0.5 (input; feedrate, output; depth, Ts = 0.5 s) (From Song and Hardt, 1992)

Process Limitation: Lack of Decoupling. In the course of this research, a consistent observation was made that has very important implications for the control of welding processes and indeed for the manufacturing processes in general. This concerns the limited control range or *reachability* of the process. In the SISO case discussed above, there is the basic saturation problem of the maximum and minimum heat input rate that can be achieved, but much more severe is the strong coupling exhibited between all of the outputs in the MIMO problem, illustrated in Fig. 4. For example, Fig. 7 shows the input-output maps for two different output pairs, and for both the actual range of feasible operation is quite limited. As a result, the control system described above, while quite capable of regulating the outputs within this narrow range, cannot move the process outside this range unless the basic process itself is modified.

In an attempt to do so, both Doumanidis and Hardt (1991) and Masmoudi and Hardt (1992) used rapid oscillation of the welding torch along or transverse to the line of travel. By doing so, the heat input distribution could be modified, thereby changing the resulting temperature distributions in the weldment and in turn changing the relative dimensions of the pool and the heat-affected zone isotherm (see Fig. 8). This increased the range of operation of the process, permitted rejection of realistic disturbances, and potentially enhances the basic productive performance of this process.

From this brief review, it is apparent that welding is a process that is amenable to numerous forms of dynamic system modeling and feedback control. However, when one concentrates on process output control the multivariable, nonlinear, highly coupled nature of the process must be dealt with. Simple single variable control designs can perform well, especially when adaptive techniques are used to deal with the nonlinear behavior (e.g., Suzuki et al., 1991). However, as detailed above, the coupling present in the existing processes precludes exploiting multivariable control to its fullest.

The origin of this problem is traced here as one of an uncontrolled temperature distribution in the weldment. Although no manner of feedback can overcome this basic physical process, rather simple process modifications (e.g., Masmoudi and Hardt, 1992) have been shown to greatly increase the process latitude. In their generalized form, they involve the distribution of a controlled heat flux into the weldment, and possibly a controlled mass and heat flux from filler material.

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[7] From Narendra and Lin (1980) but modified by Suzuki et al. (1991) to enhance stability.

[8] The technique of self-tuning control with pole-placement from Åström and Wittenmark (1984) was used.

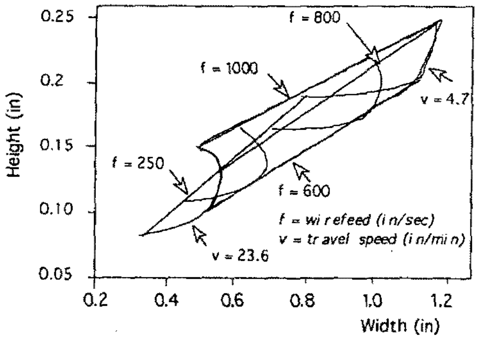


Fig. 7(*a*) Bead height/width input-output map (from Hale and Hardt, 1990)

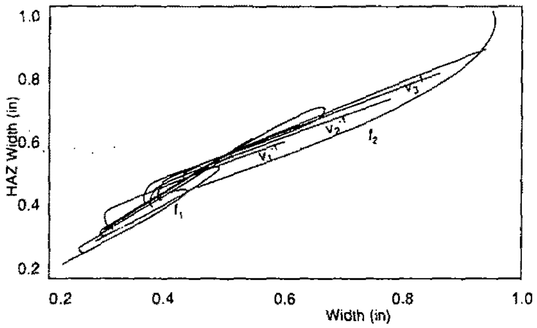
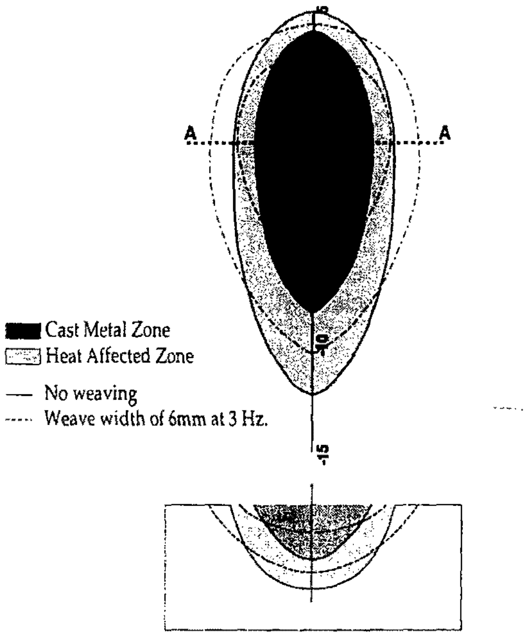


Fig. 7(*b*) HAZ-width input-output map (From Masmoudi and Hardt, 1992)

Fig. 7 Reachability for gas metal arc welding. In both cases the inputs are current (wire feedrate) and travel speed.



Section A-A

Fig. 8 Effect of high frequency torch weaving on temperature distribution for GTAW

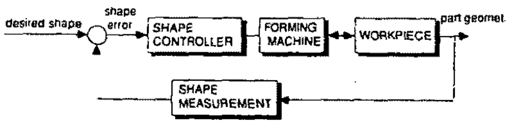


Fig. 9 Block diagram for sheet forming shape controller

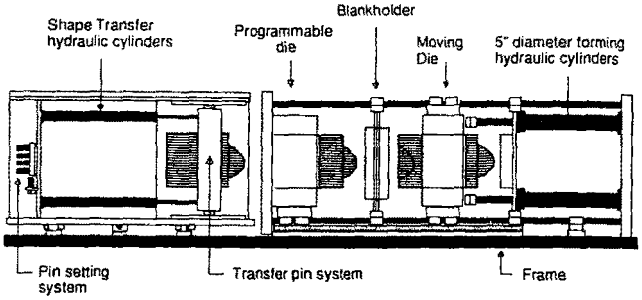


Fig. 10 Discrete die forming machine. Part shapes are programmed into the left-hand die and then transferred to the right-hand tool by "impression." The left-hand tool is then reset to the correct contour, and forming proceeds under the action of the 5 in. cylinders.

Recently a significant number of investigators in the field have applied artificial neural networks to the welding control problem for purposes of I/O modeling (e.g., Smartt, 1992; and Cook et al., 1990). Fuzzy logic controllers have also been shown to be effective in closing the loop (Smartt, 1992; Langari and Tomizuka, 1988; and Boo and Cho, 1991). However, it has yet to be shown that these techniques provide comparable performance to the methods shown above, although they may simplify the modeling requirements.

Case II: Output Control of a Parallel Process—Shape-Controlled 3D Sheet Forming

The second example involves a parallel process: sheet metal forming. The basic objectives of such a system are shown in Fig. 9, where the part shape is the output of concern.[9] Two fundamental problems are presented by the process:

- How can the process be actuated to give it sufficient degrees of freedom to permit real-time response?
- How can the process be characterized to permit design of a stable, high-performance shape controller?

The first problem arises from the parallel nature of the forming process, which typically controls shape through the shape of the tooling. This shape is *not* easily changed and if done can take hours or many days to accomplish. In this research, this problem has been addressed head-on by designing a new machine that *can* change tooling shape rapidly. In particular, a rapidly reconfigurable, discretized forming surface was developed and realized on a large scale lab device, shown in Fig. 10.

The tools themselves are 12 × 12 in. (30.5 × 30.5 mm) square arrays of 1/4 in. (13.7 mm) square pins with spherical ends. Each tool comprises 2304 such elements, and they are clamped in a housing by a hydraulic actuator with a force of 60,000 lb (270 kN). Arrangement in vertically separated columns prevents pin interaction during the setup phase and greatly minimizes static indeterminacy during clamping.

The shape is programmed by a series of position servos that adjust a single die element column at a time. Setup time for both tools is currently one (1) hour, but this time is constrained by the number (eight) and speed of the actual servos in use at this time. Smoothing of the surface is accomplished at present by sandwiching the sheet between layers of 1/4 in. thick ethylene vinyl acetate sheets that have been premolded to tools. (See Ousterhout (1991) and Eigen (1992) for details on the machine and the smoothing materials.)

Control System Analysis and Design. The second problem

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[9] No attempt is made here to control properties of the product, which are modified by phenomena such as strain hardening. However Fenn and Hardt (1992) demonstrate the use of real time control for strain and forming stability control.

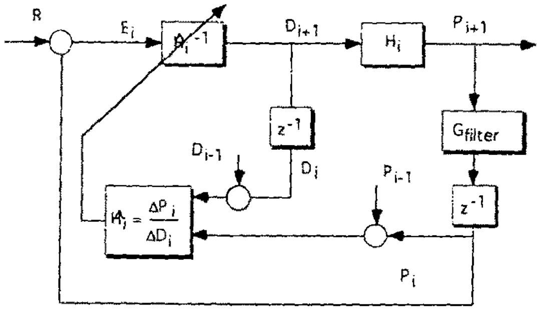

Fig. 11 Deadbeat shape controller based on estimation of *H*. The assumed sample interval is one forming cycle (index *i*).

of how to characterize the process for control was addressed by Webb and Hardt (1991) through the use of 3-D spatial Fourier transforms. The motivation was to find a shape descriptor that both captured the inherent coupling present in sheet forming and worked mathematically for controller design purposes. By transforming shape data from Cartesian coordinates to spatial frequency spectra, it is possible to create a deformation transfer function (DTF) that is defined as:

$$\mathbf{H}(\omega_1, \omega_2) = \frac{\Delta\mathbf{P}(\omega_1, \omega_2)}{\Delta\mathbf{D}(\omega_1, \omega_2)} \tag{5}$$

where ω_1, ω_2 are the spatial frequencies along the orthogonal axes of the part, $\Delta\mathbf{D}(\omega_1, \omega_2)$ is the change in the frequency spectrum of the die shape between two forming trials, and $\Delta\mathbf{D}(\omega_1, \omega_2)$ is the corresponding change in the part shape.[10]

The controller design is shown in Fig. 11, and is essentially a one-step-ahead approach based on continual identification of $H(\omega_1, \omega_2)$. The actual control law is given by:

$$D_{i+1} = D_i + E_i H_i^{-1} \tag{6}$$

where

D_i = the transform of the die shape on the *i*th forming cycle
E_i = the *i*th shape error given by $E_i = R - D_i$
$\mathbf{R}$ = transformed reference part shape

where the algorithm attempts to move the error to zero in a single time step (forming trial) based on the best current estimate of the forward-loop transfer function $\mathbf{H}(\omega_1, \omega_2)$.

Controller Implementation. The application of the shape controller to continuous-tool axisymmetric forming is rather straightforward (Webb and Hardt, 1991); however, full 3-D implementation using discrete tooling raises several issues, among which are:

- the limited spatial bandwidth of the discrete tools,
- measurement errors from the large (144 in.^{2}) surface,
- propagation of errors from tool setting, part measurement and inherent forming uncertainty.

The first of these is considered a basic bandwidth limitation imposed by the discrete tooling, and dealt with by prefiltering all desired shapes to exclude frequencies above those achievable by the system.[11] The second problem was dealt with both by spatial filtering of the measurement data and by using the power spectrum estimation methods of Welch (1978) while repeating the shape data to create a larger data set for transformation.

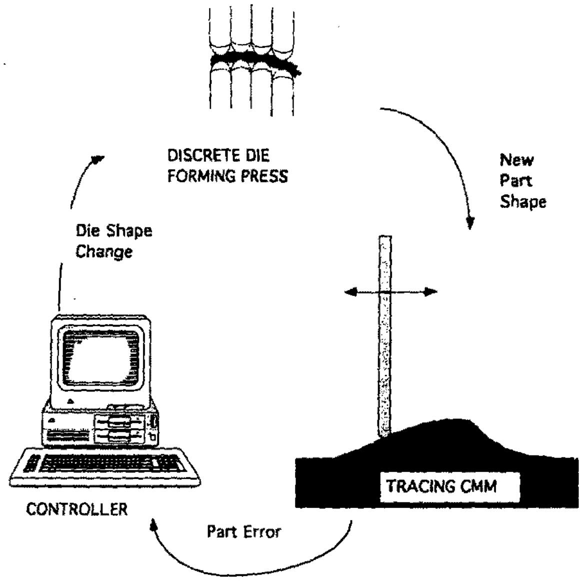

Fig. 12 The flexible sheet forming system

Controller Performance. Simulation of this control scheme requires a process model of considerable complexity. In essence, a full 3-D elastic-plastic analysis with frictional boundary conditions, and a discrete tooling surface with compliant covering, is necessary. Such a model has been developed (see Karafillis and Boyce (1991), and Hardt et al. (1992)) for 2-D axisymmetric parts, and this finite element-based model can also execute the foregoing control shape control algorithm in simulation. However, for full 3-D test, the only alternative at this time is experimentation. Accordingly, a series of experiments using the system shown in Fig. 12 and employing the algorithm of Eq. (6) were performed.

Each experiment consisted of two initial "open-loop" forming trials required to provide a first estimate of $\mathbf{H}(\omega_1, \omega_2)$. The first, P_1, was produced by setting the die surface to the reference shape (the "100 percent" tool) and the second part, P_2 was produced by setting the die surface to 110 percent of the reference shape. Once these two initial forming trials were conducted, the first, $\mathbf{H}(\omega_1, \omega_2)$, could be computed and the closed-loop forming process started. Subsequent die shapes were calculated using the control algorithm shown in Fig. 13. After a part was formed, it was measured on the tracing CMM using measurement increments of 0.0625 in. (1.6 mm).

Four different reference shapes that were prefiltered to confine the spatial frequency content to the controllable range of the machine were examined as shown in Fig. 14. Next to each part is a table showing the progress of each experiment. In all cases, the desired final shape was achieved within the error bounds of the system in no more than two closed-loop trials after the initial two start-up cycles.

Discussion

These two research examples highlight the diversity and difficulty of control problems that exist in manufacturing processes. Since the welding process is serial in nature, it lends itself to application in linear and nonlinear control and modeling methods. But ultimately the basic physical limitations of the process (such as strong output coupling), rather than the measurements or controller design, dominate the performance limitations. The sheet forming example highlights both the new realm of problems that are introduced when dealing with a

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[10] Since this approach implies linear deformation, it is only valid for small deformations near the final shape behavior; thus incremental shape changes are used (see Webb, 1987). Fortunately, this is not a severe limitation since initial tooling shape estimates usually given initial trial shapes very close to the desired shape, and only small corrections are necessary from the controller.

[11] The discrete tool is in fact capable of creating surfaces with frequencies higher than the limits imposed here = 1.0 in^{-1} or 1.0 1/in, but it was found empirically (Ousterhout, 1991) that such forming was nearly acausal with respect to die shape changes, and caused forming control system instabilities for certain shapes.

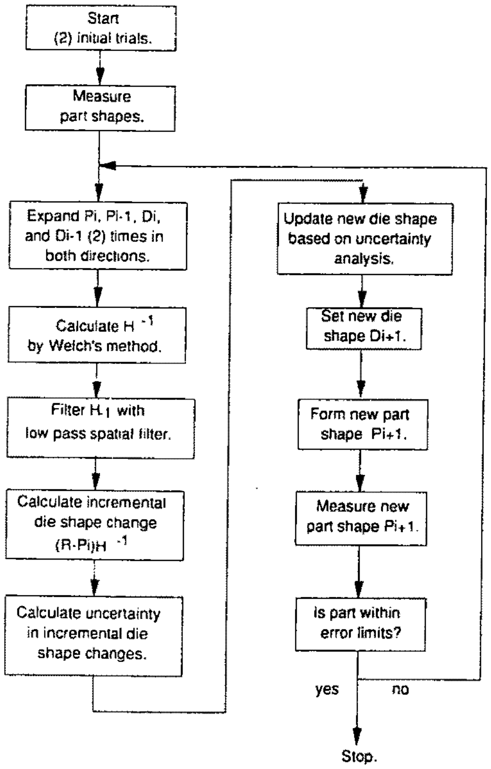
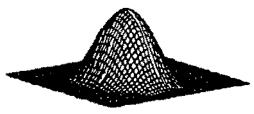
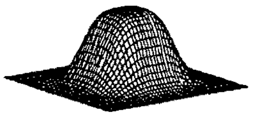


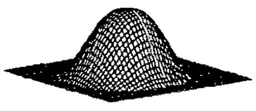
Fig. 13 Closed-loop control algorithm for experiments



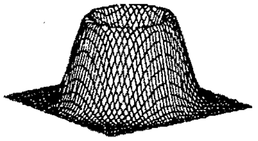
Cycle #	Maximum Error	RMS Error
#1 (startup)	0.055 (in.)	0.024
#2(startup)	-0.034	0.016
#3(closed-loop)	0.041	0.015
#4 closed-loop)	0.020	0.007



Cycle #	Maximum Error	RMS Error
#1 (startup)	-0.180 (in.)	0.061
#2(startup)	-0.379	0.154
#3(closed-loop)	-0.052	0.017
#4 closed-loop)	0.026	0.010



Cycle #	Maximum Error	RMS Error
#1 (startup)	0.057 (in.)	0.032
#2(startup)	-0.047	0.014
#3(closed-loop)	0.022	0.008
#4 closed-loop)	0.023	0.009



Cycle #	Maximum Error	RMS Error
#1 (startup)	-0.051 (in.)	0.023
#2(startup)	-0.054	0.016
#3(closed-loop)	0.045	0.012
#4 closed-loop)	-0.034	0.011

Fig. 14 Results of closed-loop sheet forming experiments

spatially distributed geometry control problem (the parallel process) and the need to develop entirely new control methods for such processes. While rather extensive numerical modeling of sheet deformation processes is now possible (for example, see Karafillis and Boyce, 1991) such modeling methods are not directly useful for control system design, and new methods, such as the *deformation transfer function* approach discussed here are necessary.

What links these two cases is the necessity of process (re)design in order to reach the true potential of "controlled processes." This requires that dynamics and control researchers move well beyond the boundaries of measurement and control to become intimately involved with the physically and detailed design of the next generation of manufacturing processes. The discrete tooling concept presented above is one example of how control objectives have led to design of entirely new processes.

Another growing area of process redesign for control is the "serialization" of processes that are conventionally parallel in nature. The best known of these are the new rapid prototyping methods such as *stereolithography* (Kodama, 1981; and Hull, 1986), *laser sintering* (Deckard, 1989) and *3-D* printing (Sachs et al., 1990). These are all examples of taking parallel process physics and converting it to a serial process. Stereolithography is effectively a solidification process performed locally using light induced polymerization. The region of reaction is then traced *serially* throughout the volume of the liquid until a complete solid part is produced, as opposed to filing a mold and then letting the entire mass react. Laser sintering does essentially the same thing, but selectively binds metal particles together in a serial fashion. Again, this contrasts with the conventional practice creating a green compact in a model and then sintering the entire mass simultaneously. Finally, in the process of three-dimensional printing, a binder is serially applied to a bed of ceramic powder, serially creating the part volume, replacing powder molding, and compacting steps that require tooling and afford little control. Such processes immediately create a large amount of control authority and great flexibility in controlling both geometry and local properties. This continued development depends directly on both machine control innovations and on better understanding of the process dynamics and its control.

Summary and Conclusions

The match between modeling and control methods and the objectives of manufacturing processes is clear and strong. Yet we in the dynamics and control community have not had a dominant influence on the progress of manufacturing processes or process control. Most of our work has concentrated on processes that are serial in nature, which in turn prove to be amenable to conventional control methods. Modeling, identification, and closed-loop methods can be applied to a much broader range of manufacturing processes, but only if the basic physical constraints on control imposed by the process are carefully examined and the process is redesigned as necessary. Whatever the approach, it is the role of the process control designer to decide upon the appropriate level of control desired, always keeping in mind that the ultimate manufacturing objective is the control of the output geometry and properties.

Despite the clear need, to date, the dynamics and control community has not attacked manufacturing processes in a comprehensive fashion. I believe this can be traced to the difficulty of implementing and executing control methods in many existing processes. Perhaps the best example of this is the serial-parallel process tradeoff. The serial process is inherently flexible and controllable, but the parallel process has proved to be far more productive. Perhaps the ultimate manufacturing process—one that can produce precise one-of-a-kind parts at high production rates—will have to wait until both new modeling and control methods, and new processes based on these methods, emerge. . . or perhaps until Herb takes aside a few more green assistant professors and tells them "how it is."

Acknowledgments

The research from which this paper derives has resulted from the efforts of many people, and I wish in particular to ac-

knowledge the tireless work of the nearly 60 graduate students I have had the pleasure to work with over the past 15 years. Each contributed his or her insights to the puzzle described in this paper, and none of this would have existed without them.

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