# II MACHINE DESIGN FOR PRECISION MANUFACTURING

## 2.1 Background on machine design for manufacturing

The development of machines over time can be viewed through a number of different lenses. Shirley and Jaikumar[16], for example, refer to a classification of seventeen levels of mechanization of "machines" related to their power and control sources. These developments, or levels, roughly follow progress of man and machine through time. So one sees the development from a person holding a tool at the lowest level, level 2 (level 1 being the person's hand alone) through powered tools to more automated machinery. Finally, at level seventeen, we see a machine which anticipates action required and adjusts itself to provide it in response to some sensor inputs and "intelligence" containing an objective function and means for optimization.

Moriwaki has represented this development in a more engineering-oriented fashion. Figure 2.1, from Moriwaki[17], describes the transition from the machine driven by "predetermined commands" which is much more than open loop — here implying even so-called adaptive control, but control about some pre-determined set of operating conditions based on our best estimate of the required conditions and the existent material, tooling and work geometry circumstances. Crossing the magic dotted line in the figure signifies machines which can make decisions "for themselves." What this rather anthropomorphic term implies is that, based on ambiguous or incomplete information, experience (codified in data bases or process models), as well as an ability to "learn" from conditions experienced while in operation, the machine and controller can process this array of information and determine the best course of action to achieve the objective. The objective is usually the creation of a surface with certain characteristics, artifacts with dimensions within certain tolerances and error of form within other bands. Whether or not one chooses to believe this characterization, the image in the figure does represent the views pertaining to the direction of development of machinery for manufacturing.

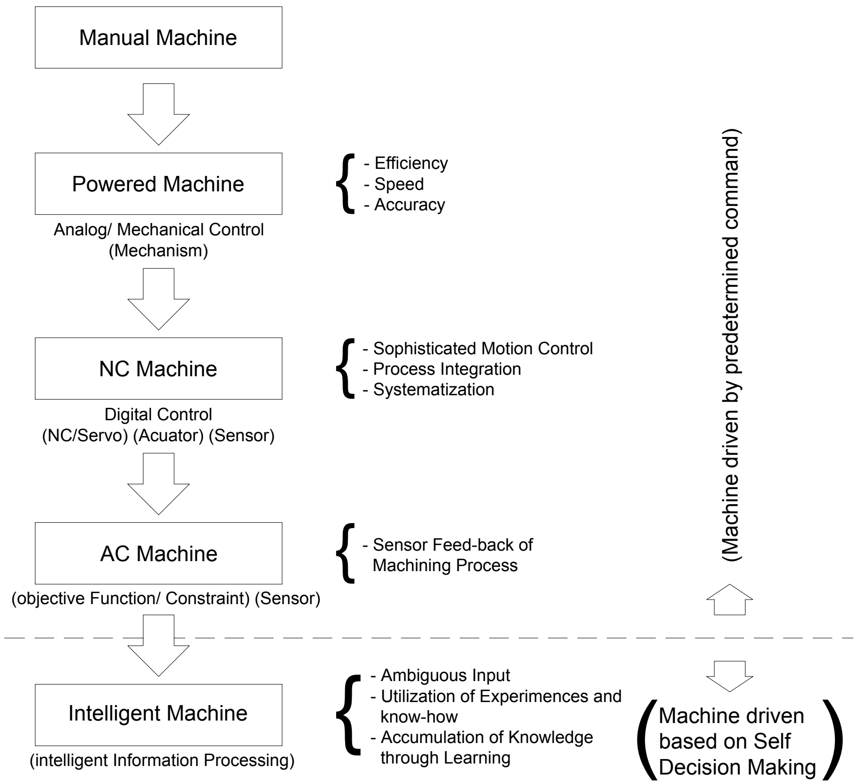


**Figure 2.1.** History of machine tool development, from Moriwaki[17].

The view outlined in the previous paragraph creates tremendous challenges for the precision manufacturing engineer. It pushes the requirement on "determinism" to the limit as we try to insure the performance of complex mechanisms over ever broadening ranges of performance. Certain design strategies will be employed to insure that determinism is achieved to the extent possible. The "natural enemies" complicating the task are the errors in these mechanisms. These will be introduced after a brief discussion of design philosophy.

## 2.2 Philosophy of precision machine design

The purpose of this chapter is not to present design philosophies for machines in any detail but, rather, to set the stage for our discussion on precision machinery for manufacturing. This may seen like an arbitrarily fine distinction but there are excellent texts available to which the reader is referred for more on that subject. Specific sources include Slocum[18] and Nakazawa[19] which give very detailed and practical (in the case of Slocum) and more philosophical (in the case of Nakazawa) information on precision machine design. There are many other general texts which cover the principles of design, from identification of functional requirements through project management. The unique features of precision machines or the processes they implement must be considered.

The success or failure of a precision machine can be evaluated with respect to six major items, from Nakazawa[19], all of which will be discussed in more detail. These are:

- dimensional precision
- angular precision
- form precision
- surface roughness
- kinematic precision
- surface layer alterations

These are both elements that must be *designed in* to the machine as well as features or characteristics of machine performance that must be *measured*. Nakazawa describes in some detail methods for insuring that the proposed design solution, building on the functional requirements of the machine or system, can be obtained in the most efficient, mechanically, and cost effective, economically, way. Finally, Nakazawa establishes a set of design principles which are illustrated in the text with specific machine elements or systems. The design principles revolve around the needs for precision machines to meet the four basic functional requirements, Nakazawa[19], of:

- possessing a perfect kinematic reference,
- possessing a perfect kinematic pair which execute perfect movement with respect to the reference,
- being constructed so as to prevent noise (or disturbances) in operation, and
- being able to detect movement accurately.

Some of these principles are derived from basic theories we will be covering later in the text.

Nakazawa's first design principle is the principle of functional independence and states[19]:

"When controllable functional requirements exist, a system in which the functions are independent is preferable to one in which the functions are not independent."

The principle of functional independence was proposed by Suh[20] and applies to a wide range of systems. Nakazawa's second design principle[19] is the principle of total design:

"When constraints exist for certain evaluational items, total design is better than either additive design or combination design."

For example, it may be better to design a wholly new machine tool to meet the six critical characteristics than to modify an existing design or assemble a machine from existing components. Of course, this may cost more initially.

One final reference that is not easily obtainable but offers invaluable insight into the philosophy and practice of design and manufacture of precision machinery is by Moore[21]. Moore's company, Moore Special Tool Company, is arguably one of the finest precision machine makers in the world. Moore Special Tool started in 1924 as a specialty tool making shop in Bridgeport CT making tooling for watch, clock and typewriter plants. Moore approaches the challenge from the point of view of the skilled machine builder and picks up where Nakazawa leaves off. That is, Moore answers the question...okay, so how do we actually build this machine we have so cleverly designed? And, further, how do we prove we built it? Moore emphasizes the need to master what he refers to as "the four mechanical arts:"[21]

- geometry (starting with it's foundation in the flat plane, from which the surface plate evolves and straightedges, and methods of scrapping them)
- standards of length (referring here to the measuring element of a machine tool — the lead screw — from which the machine derives its accuracy)
- dividing the circle (being able to accurately divide the circle is a challenge that has confronted precision machine and instrument makers for centuries, see Evans[1], for excellent background on this.)
- roundness (the performance of these machines is dependent upon the overall accuracy of holes, shafts, balls and other components of the machine.)

We will return to these mechanical arts throughout the course.

## 2.3 Sources of error - overview

We referred to the sources of errors in precision machine as "natural enemies" of the precision engineer. Recall Donaldson's and Bryan's insistence on determinism in design — that is, the application of sound engineering analysis to overcome the errors in performance of these mechanisms. Taniguchi had referred to these as "systematic errors" with the errors that had no obvious or repeatable clear source as “random errors.” It all boils down to how closely (and how much time/money spent) one wants to look for the sources of errors *or* utilize methods of design and manufacture to prevent or minimize the errors. We declare victory over errors when they are either not measurable or measurably small enough to fall below our specifications.

Machine tools, which are a good focus for our discussion as they have all of the critical elements of interest (as well as create all of the critical elements on the workpiece), are basically closed structural frames, Figure 2.2. The spindle, in which the tool is mounted for material removal, is linked to the frame, here comprised of the column, base and table, which supports the workpiece. One can easily imagine the corresponding sketch components for a lathe or other machine. The critical “open” connection in this loop is between the work surface and the tool. Clearly, any error in position between tool and work surface will result in a dimensional error on the part surface (tolerance, form, surface, sub-surface damage, etc.) Thus, anything that contributes to an error in position is of concern us. We will describe the frame of reference for quantifying the errors in position as you can imagine they are both translational as well as well as rotational. And, they will be most troublesome in certain directions, called *sensitive directions* — for example, perpendicular to the surface of a machined part.

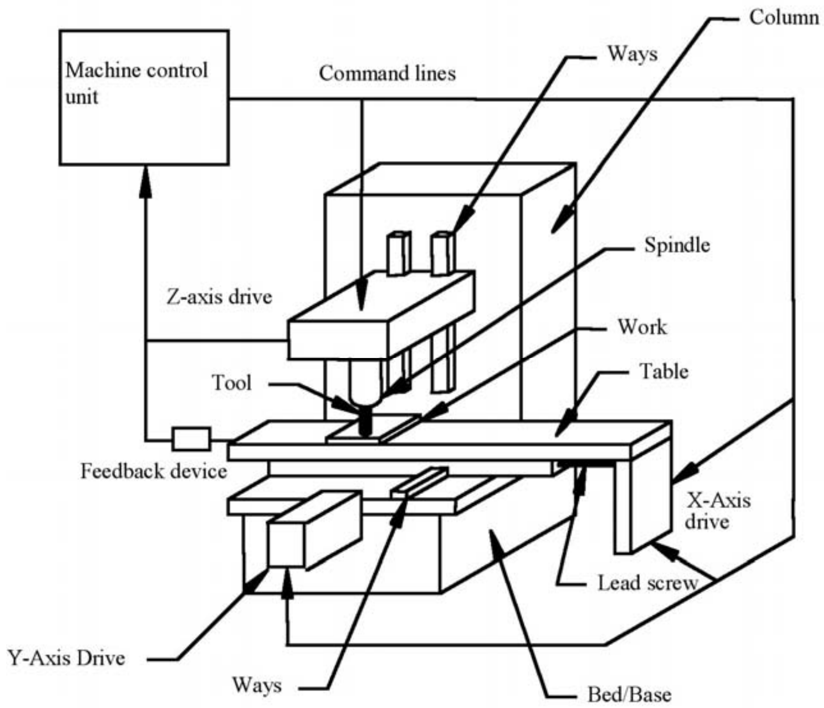


**Figure 2.2.** Machine tool structural "loop".

In the past, many efforts have been made to characterize the errors in part features, holes and planes, in terms of process parameters. This was done to aid in process planning methodology which generally attempts to map processes on to features for the selection of the minimum set of processes and their sequence of use to create a machined part. Often this is referred to as process capability analysis. Wysk[22] introduced a "process boundary table" which defines for hole and plane producing operations tolerances on dimension and form. These are determined based upon statistical regression fits of data (that is a slope and intercept for linear relationships and exponents and intercepts for nonlinear relationships) based upon intuitive analysis, simulation and/or experimental evidence. Basically, tool position errors for plane generation due to setup or inaccurate measurement of tool length or diameter provide a constant offset or intercept and machining conditions, like metal removal rate, provide a variable input. Tolerances on hole diameters (diameter only, not form such as cylindricity or perpendicularity) are estimated similarly, Scarr[23]. These are of the form

$$\text{Tolerance} = A\,(D)^{n} + B \qquad (2.1)$$

where: A = coefficient of the process (say drilling)
n = exponent describing the process (sensitivity of process parameters on hole tolerance for a specific diameter)
B = constant describing the best tolerance attainable by the process (and here this could refer to the drill geometry, specifically, and tolerance on the drill diameter as these will have the largest influence on diameter)
D = diameter of the hole

Tool deflection will cause errors in straightness and parallelism so tool length (often normalized by diameter) will appear as a dependent variable. For face milling operations, tool deflection (at a certain tool length but driven by material removal rate — to which tool forces are generally proportional) and the corresponding out of plane deflection of the face of the milling cutter is useful for estimating surface roughness. Think of a rotary lawn more with a bent blade shaft passing over a lawn. The "sawtooth" appearance that results is exactly the same as the surface of a workpiece machined by a deflected face milling cutter. Recently, a number of researchers have developed very sophisticated software programs for predicting these effects in an attempt to better plan the process to meet design specifications; see DeVor[24], for example. Figure 2.3, from the Machine Tool Task Force Study[25], summarizes one prevailing view of the feedback from the process to control machine performance. This, as with most other schemes, still operates at the "pre-determined command" state described by Moriwaki.

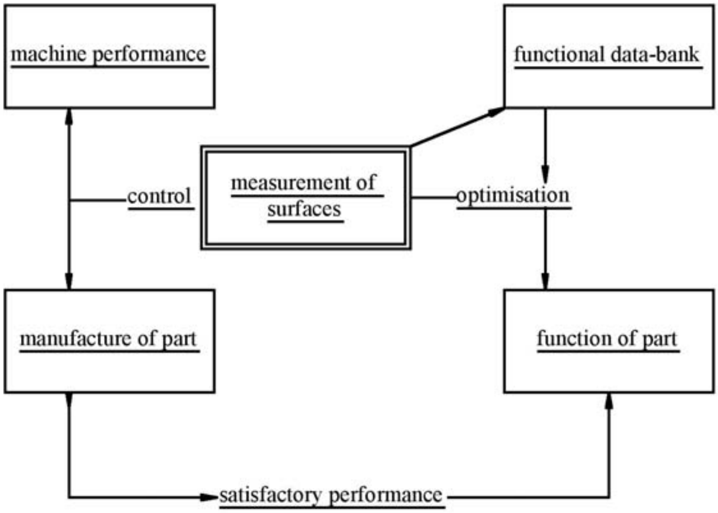


**Figure 2.3.** Process feedback for manufacturing, from MTTF[25].

As interesting and useful as these estimates of process capability, they are reactive rather than proactive. That is, they try to predict the performance by measuring and modeling the part features. For precision manufacturing, this is seldom effective and can, in fact, confuse the issue by masking interaction effects. Hence, we are interested in the sources of errors and the extent to which we can understand, model and predict the magnitude and direction of their effects. The study by Shirley and Jaikumar[16] also summarized common sources of error in machine tools using the Taniguchi classification of "systematic" and "random." They also included "dynamic" with random but Taniguchi would call this random as well. Classification of errors in machine tools are categorized as mechanical and thermal operational errors with respect to those on the part and those on the machine. They also include operational errors which, basically, cover all other errors from programming the controller to sloppy tool holders to measurement errors as with a coordinate measurement machine. From the point of view of determinism, the systematic errors are most repeatable and predictable while the so-called random/dynamic errors are not. As we will see, most of the errors in their random column are, in fact, predictable (or if not, can at least be bounded).

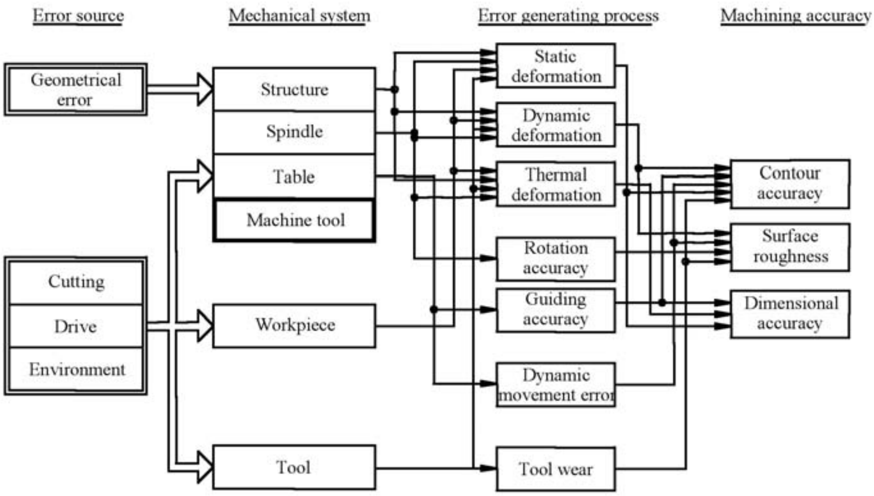


**Figure 2.4.** Machining error generating process, from Wada[26].

A more instructive view of error sources and their effects is shown in Figures 2.4 and 2.5, both from Wada at a Japanese machine tool engineer's conference[26]. Figure 2.4 constructs a "fault tree analysis" of the source of measurable errors in three of the most critical features on the machined part, contour or form accuracy, surface roughness and dimensional accuracy. It traces the accuracy back to the "process" generating the error, such as static deformation or tool wear, and associates it with the likely mechanical system elements in which the error generation occurs, such as a spindle or table (as part of the machine tool). It includes the other elements of the machine tool loop as well, the workpiece and the tool. We will see that diagrams such as this one, with measures of influence placed on the lines connecting one box to the other, will be the basis of our development of quantitative "error budgets" for machine design later in the notes.

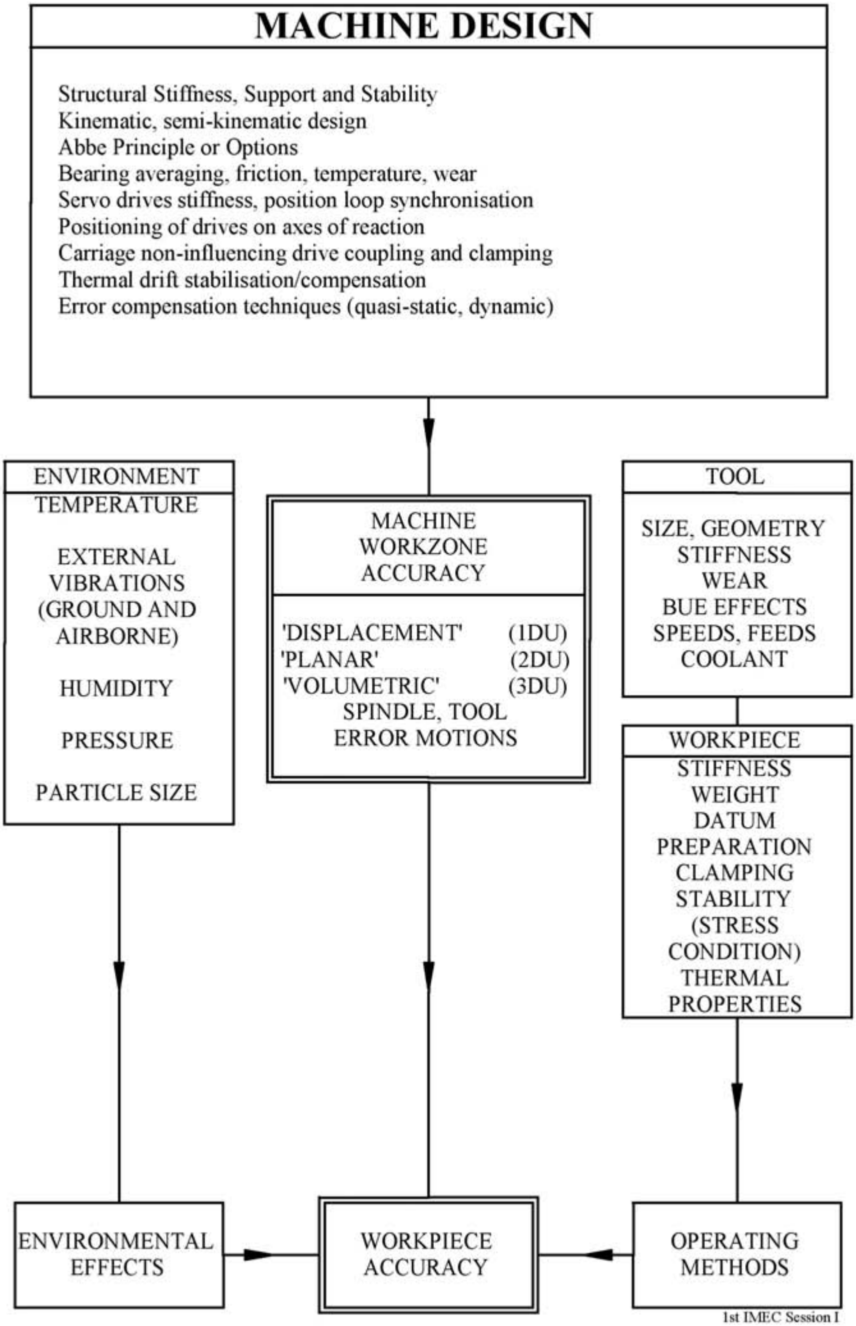


**Figure 2.5.** Factors affecting workpiece accuracy, from Wada[26].

Figure 2.5 is a detailed view of the specific contributors to workpiece accuracy from the point of view of the machine design (mapped on to the machine workzone accuracy), the environment in which the machine operates, tool characteristics and workpiece characteristics. This figure describes the “to do” list for precision machine tool design for manufacturing. Of interest to us will be the methods of quantifying these contributing sources, estimating their cumulative effect (most can be superposed), and determining how to minimize or eliminate their effects. Process related contributors are listed here under tool and workpiece but this does not give complete treatment to their impact and will be treated in more detail as well. The most significant point to be made from these two figures is that it is possible to trace the dimensional, contour and surface accuracy of a workpiece back to specific machine elements through the error generating mechanisms at work. With that knowledge, we can proactively design machines and processes for precision manufacturing.

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