1.5 IMPACTS OF AUTOMATION ON PRECISION[1]

M. Alkan Donmez and Johannes A. Soons
Manufacturing Engineering Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

ABSTRACT

Automation has significant impacts on the economy and the development and use of technology. In this section, the impacts of automation on precision, which directly influences science, technology, and the economy, are discussed. As automation enables improved precision, precision also improves automation.

Followed by the definition of precision and the factors affecting precision, the relationship between precision and automation is described. This section concludes with specific examples of how automation has improved the precision of manufacturing processes and manufactured products over the last decades.

1.5.1 What is precision

Precision is the closeness of agreement between a series of individual measurements, values, or results. For a manufacturing process, precision describes how well the process is capable of producing products with identical properties. The properties of interest can be the dimensions of the product, its shape, surface finish, color, weight, etc. For a device or instrument, precision describes the invariance of its output when operated with the same set of inputs. Measurement precision is defined by the International Vocabulary of Metrology [1] as the "closeness of agreement between indications obtained by replicate measurements on the same or similar objects under specified conditions." In this definition, the "specified conditions" describe whether precision is associated with the repeatability or the reproducibility of the measurement process. Repeatability is the closeness of the agreement between results of successive measurements of the same quantity carried out under the same conditions. These repeatability conditions include the measurement procedure, observer, instrument, environment, etc. Reproducibility is the closeness of the agreement between results of measurements carried out under changed measurement conditions. In computer science and mathematics, precision is often defined as a measure of the level of detail of a numerical quantity. This is usually expressed as the number of bits or decimal digits used to describe the quantity. In other areas, this aspect of precision is referred to as resolution: the degree to which nearly equal values of a quantity can be discriminated, the smallest measurable change in a quantity, or the smallest controlled change in an output.

Precision is a necessary but not sufficient condition for accuracy. Accuracy is defined as the closeness of the agreement between a result and its 'true' or intended value. For a manufacturing process, accuracy describes the closeness of the agreement between the properties of the manufactured products and the properties defined in the product design. For a measurement, accuracy is the closeness of the agreement between the result of the measurement and a true value of the measurand – the quantity to be measured [1]. Accuracy is affected by both precision and bias. An instrument with an incorrect calibration table can be precise, but it would not be accurate. A challenge with the definition of accuracy is that 'true value' is a theoretical concept. In practice, there is a level of uncertainty associated with the true value due to the infinite amount of information required to completely describe the measurand. To the extend that it leaves room for interpretation, the incomplete definition of the measurand introduces uncertainty in the result of a measurement, that may or may not be significant relative to the accuracy required of the measurement. For example, suppose the measurand is the thickness of a sheet of metal. If this thickness is measured using a micrometer caliper, the result of the measurement may be called the best estimate of the 'true value', 'true' in the sense that it satisfies the definition of the measurand. However, had the micrometer caliper been applied to a different part of the sheet of material, the realized quantity would be different with a different 'true value' [2]. Thus the lack of information about where the thickness is defined, introduced an uncertainty in the 'true value'. At some level, every measurand or product design has such an "intrinsic" uncertainty.

1.5.2 Precision as an enabler of automation

Historically, precision is closely linked to automation through the concept of parts interchangeability. In more recent times, it can be seen as a key enabler of lean manufacturing practices. Interchangeable parts are parts that conform to a set of specifications that insure that they can substitute each other. The concept of interchangeable parts radically changed the manufacturing system used in the first phase of the industrial revolution, the English system of manufacturing. The English system of manufacturing was based on the traditional artisan approach to making a product. Typically, a skilled craftsman would manufacture an individual product from start to finish before moving on to the next product. For products consisting of multiple parts, the parts were modeled, hand fitted, and reworked to fit their counterparts. The craftsmen had to be highly skilled, there was no automation, and production was slow. Moreover, parts were not interchangeable. If a product failed, the entire product had to be sent to an expert craftsman to make custom repairs, including fabrication of replacement parts that would fit their counterparts.

Pioneering work on interchangeable parts occurred in the printing industry (movable precision type), clock and watch industry (toothed gear wheels), and armories (pulley blocks and muskets) [3]. In the mid to late 18th century, French General Jean Baptiste Vaquette de Gribeauval promoted the use of standardized parts for key military equipment such as gun carriages and muskets. He realized that interchangeable parts would enable faster and more efficient manufacturing, while facilitating repairs in the field. The development was enabled by the introduction of two dimensional mechanical drawings, providing a more accurate expression of design intent, and increasingly accurate gauges and templates (jigs), reducing the craftsman's room for deviations while allowing for lower skilled labor. In 1778, master gunsmith Honoré Blanc produced the first set of musket locks completely made from interchangeable parts. He demonstrated that the locks could be assembled from parts selected at random. Blanc understood the need for a hierarchy in measurement standards through the use of working templates for the various pieces of the lock and master copies to enable the reconstruction of the working templates in the case of loss or wear [3]. The use of semi-skilled labor led to strong resistance from both craftsmen and the Government, fearful of the growing independence of manufacturers. In 1806, the French Government reverted back to the old system, using the argument that workers who don't function as a whole cannot produce harmonious products.

Thomas Jefferson, a friend of Blanc, promoted the new approach in the United States. Here the ideas led to the American system of manufacturing. The American system of manufacturing is characterized by the sequential application of specialized machinery and templates (jigs) to make large quantities of identical parts manufactured to a tolerance (see e.g., [4]). Interchangeable parts allow the separation of parts production from assembly, enabling the development of the assembly line. The use of standardized parts furthermore facilitated the replacement of skilled labor and hand tools with specialized machinery, resulting in the economical and fast production of accurate parts.

The American system of manufacturing cannot exist without precision and standards. Firstly, the system requires a unified, standardized method of defining nominal part geometry and tolerances. The tolerances describe the maximum allowed deviations in actual part geometry and other properties that ensure proper functioning of the part, including interchangeability. Secondly, the system requires a quality control system, including sampling and acceptance rules, and gauges calibrated to a common standard to ensure that the parts produced are within tolerance. Thirdly, the system requires manufacturing processes capable of realizing parts that conform to tolerance. It is not surprisingly that the concept of interchangeable parts first came into widespread use in the watchmakers industry, an area used to a high level of accuracy [5].

Precision remains a key requirement for automation. Precision eliminates fitting and rework, enabling automated assembly of parts produced across the globe. Precision improves agility by increasing the range of tasks that unattended manufacturing equipment can accomplish, while reducing the cost and time spend on production trials and incremental process improvements. Modern manufacturing principles such as lean manufacturing, agile manufacturing, just in time manufacturing, and zero-defect manufacturing cannot exist without manufacturing processes that are precise and well-characterized.

Automated agile manufacturing, for example, is dependent upon the solution of several precision-related technical challenges. Firstly, as production machines become more agile, they also become more complex, yet precision must be maintained or improved for each of the increasing number of tasks that a machine can perform. The design, maintenance, and testing of these machines becomes more difficult as the level of agility increases. Secondly, the practice of trial runs and iterative accuracy improvements is not cost-effective when batch sizes decrease and new products are introduced at increasing speeds. Instead, the first and every part have to be produced on time and within tolerance.

Accordingly, the characterization and improvement of the precision of each manufacturing process becomes a key requirement for competitive automated production.

1.5.3 Automation as an enabler of precision

As stated by Portas, "Random results are the consequence of random procedures" [6]. In general, "random results" appear to be random due to a lack of understanding of cause-and-effect relationships and a lack of resources for controlling sources of variability. For example, an instrument may generate a measurement result that fluctuates over time. Closer inspection may reveal that the fluctuations result from environmental temperature variations that cause critical parts of the instrument to expand and deform. The apparent random variations can thus be reduced by tighter environmental temperature control, use of design principles and materials that make the device less sensitive to temperature variations, or application of temperature sensors and algorithms to compensate thermal errors in the instrument reading.

Automation has proven to be very effective in eliminating or minimizing variability. Automation reduces variability associated with human operation. Automation furthermore enables control of instruments, processes, and machines with a bandwidth, complexity, and resolution unattainable by human operators. While humans plan and supervise the operation of machines and instruments, the craftsmanship of the operator is no longer a dominant factor in the actual manufacturing or inspection process.

1.5.4 Cost and benefits of precision

Higher precision requires increased efforts to reduce sources of variability or their effect. Parts with tighter tolerances are therefore more difficult to manufacture and more expensive to produce. In general, there is a belief that there exists a nearly exponential relationship between cost and precision, even when new equipment is not needed. However, greater precision does not necessarily imply higher cost when the total manufacturing enterprise, including the final product, is examined [7, 8].

The benefits of higher precision can be separated into benefits for product quality and benefits for manufacturing. Higher precision enables new products and new product capabilities. Other benefits are better product performance (e.g., longer life, higher loads, higher efficiency, less noise and wear, better appearance and customer appeal), greater reliability, easier repair (e.g., improved interchangeability of parts), and opportunities for fewer and smaller parts. For example, the improvements in the reliability and fuel efficiency of automobiles have to a large extend been enabled by increases in the precision of manufacturing processes and equipment. The benefits of higher precision for manufacturing include lower assembly cost (less selective assembly, elimination of “fitting” and rework, automated assembly), better interchangeability of parts sourced from multiple suppliers, lower inventory requirements, less time and cost spend on trial production, fewer rejects, and improved process consistency.

1.5.5 Measures of precision

To achieve precision in a process means that the outcome of the process is highly uniform and predictable over a period of time. Since precision is an attribute to a series of entities or process outcomes, statistical methods and tools are used to describe precision. Traditional statistical measures such as mean and standard deviation are used to describe the average and dispersion of the characteristic parameters. International standards and technical reports provide guidance about how such statistical measures are applied for understanding of the short-term and long-term process behavior and for management and continuous improvement of processes [9, 10, 11, 12].

Statistical process control is based on a comparison of current data with historical data. Historical data is used to build a model for the expected process behavior, including control limits for measurements of the output of the process. Data is then collected from the process and compared to the control limits to determine if the process is still behaving as expected. Process capability compares the output of an in-control process to the specification limits of the requested task. The *Process Capability Index*, C_p, describes the process capability in relation to specified tolerance:

$$C_p = (U - L) / 6\sigma \qquad (1)$$

where U is the upper specification limit

L is the lower specification limit

σ is the standard deviation of the dispersion

(Note that in the above equation 6σ corresponds to the reference interval of the dispersion for normal distribution, for other types of distribution the reference interval is determined based on the well-established statistical methods)

The *Critical Process Capability Index*, C_{pk}, also known as the *Minimum Process Capability Index*, describes the relationship between the proximity of mean process parameter of interest to the specified tolerance:

$$C_{pk} = \min (C_{pkL} , C_{pkU}) \qquad (2)$$

where,

$$C_{pkU} = (U - \mu) / 3\sigma \qquad (3)$$

$$C_{pkL} = (\mu - L) / 3\sigma \qquad (4)$$

μ is the mean of the process parameter of interest

1.5.6 Factors that affect precision

In case of manufacturing processes, there are many factors affecting precision of the outcome. They are associated with expected and unexpected variations in environment, manufacturing equipment and process as well as the operator of the equipment. For example, ambient temperature changes over time or temperature gradients in space cause changes in performance of manufacturing equipment, which in turn cause variations in the outcome [13,14]. Similarly, variations in workpiece material such as local hardness variations, residual stresses, deformations due to clamping or process induced forces contribute to the variations in critical parameters of finished product. Process induced variations include wear or catastrophic failures of cutting tools used in the process, thermal variations due to the interaction of coolant, workpiece and the cutting tool, as well as variations in the set locations of tools used in the process (e.g. cutting tool offsets). In case of manufacturing equipment, the performance variations due to thermal deformations, static and dynamic compliances, influences of foundations and ineffective maintenance are the contributors to the variations in product critical parameters. Finally, the variations caused by the operator of the equipment due to insufficient training, motivation, care, or information needed constitute the biggest source of unexpected variations and therefore the precision of the manufacturing process.

1.5.7 Specific examples and applications in discrete part manufacturing

The effect of automation on improving of precision of discrete part manufacturing can be observed in many applications such as improvements in fabrications, assembly and inspection of various components for high-value products. In this section one specific perspective is presented using the example of machine tools as the primary means of precision part fabrication.

1.5.7.1 Evolution of Numerical Control and its effects on machine tools and precision

The development of numerically controlled machines is a major revolution of automation in manufacturing industry. Metal cutting machine tools are used to produce parts by removing material from a part “blank”, a block of raw material, according to the final desired shape of that part. In general, machine tools consist of components that hold the workpiece and the cutting tool. By providing relative motion between these two, a machine tool generates a cutting tool path which in turn generates the desired shape of the workpiece out of a part blank. In early generation machine tools, the cutting tool motion is controlled manually (by crank wheels rotating the leadscrews), therefore the quality of the workpiece was mostly the result of the competence of the operator of the machine tool. Before the development of numerical controlled machine tools, the complex contoured parts were made by drilling closely spaced holes along the desired contour and then manually finishing the resulting surface to obtain specified surface finish. This process was very time consuming and prone to errors in locating the holes, which utilized cranks and leadscrews to manually control the orthogonal movements of the work table. For example, the best reported accuracy of airfoil shapes using such techniques was ± 0.175 mm [15]. Later generation of machine tools introduced capabilities of moving the cutting tool along a path by tracing a template using mechanical or hydraulic mechanisms thus reducing the reliance on operator competence [16]. On the other hand creating accurate templates was still a main obstacle to achieving cost-effective precision manufacturing.

Around late 1940s the U.S. Air Force needed more precise parts for its high-performance (faster, highly maneuverable and heavier) aircraft program (in the late 1940s the target was around ± 0.075 mm). There was no simple way to make wing panels to meet the new accuracy specifications. Manufacturing research community and industry had come up with a solution by introducing numerical control automation to general purpose machine tools. In 1952, the first numerically controlled 3-axis milling machine utilizing a paper tape for programmed instructions, vacuum-tube electronics and relay-based memory was demonstrated by the Servomechanism Laboratory of the MIT [17]. This machine was able to move three axes in coordinated fashion with a speed of about 400 mm/min and a control resolution of 1.25 micrometer. The automation of machine tools was so effective in improving the accuracy and precision of complex shaped aircraft components that by 1964 nearly 35,000 numerically controlled machine tools were in use in the U.S.

Automation of machine tools by numerical control led to the reduction of the need for complex fixtures, tooling, masters and templates and replaced by simple clamps resulting in significant savings by industry. This was most important for complex parts where human error was likely to occur. With the numerical control, once the control program was developed and checked for its accuracy, the machine would work indefinitely making the same parts without any error.

1.5.7.2 Enablers to improve precision of motion

Numerically controlled machine tools rely on sensors that detect positions of each machine component and convert them into digital information. Digital position information is used in control units to control actuators to properly position the cutting tool with respect to the workpiece being cut. The precision of such motion is determined by the resolution of the position sensor (feedback device), digital control algorithm and mechanical and thermal behavior of the machine structural elements. Note that, contrary to manual machine tools, operator skill, experience, and dexterity are not part of the determining factors of the precision of motion. With proper design and environmental controls, it has been demonstrated that machine tools with numerical control could achieve the levels of precision on the order of 1 micrometer or less [18, 19].

1.5.7.3 Modeling and predicting machine behavior and machining

In most material removal based manufacturing processes, the workpiece surfaces are generated as a time record of the position of the cutting tool with respect to the workpiece. The instantaneous position of the tool with respect to the workpiece is generated by the multiple axes of the manufacturing equipment moving in a coordinated fashion. Although the introduction of numerical control (NC) and later computer numerical control (CNC) has removed the main source of variation in part quality – manual setups and operations, the nature of complex structural characteristics of machines providing multi-degree-of-freedom motion, and influences of changing thermal conditions within the structures as well as the production environment still result in undesired variations leading to reduced precision of products.

Specifically, machine tools are composed of multiple slides, rotary tables and rotary joints, which are usually assembled on top of each other, each designed to move along a single axis of motion providing either a translational or a rotational degree-of-freedom. In reality, each moving element of a machine tool has error motions in six degrees-of-freedom, three translations and three rotations (see Figure 1).

Depending on the number of axes of motion, a machine tool can, therefore, have as many as 30 individual error components. Furthermore, the construction of moving slides and their assemblies with respect to each other introduce additional error components such as squareness and parallelism between axes of motion.

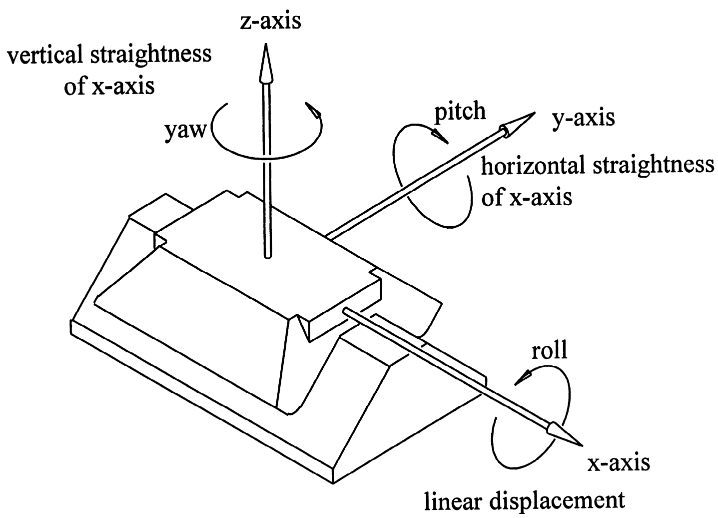
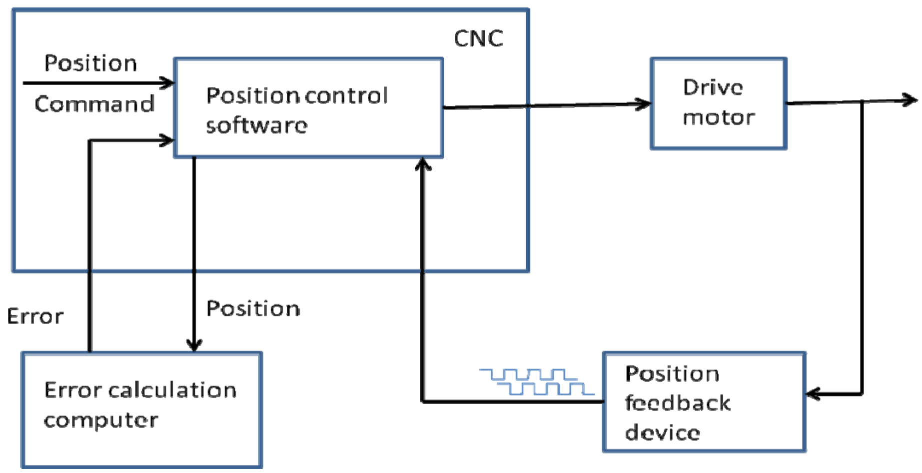


Figure 1 – Six error components of a machine slide

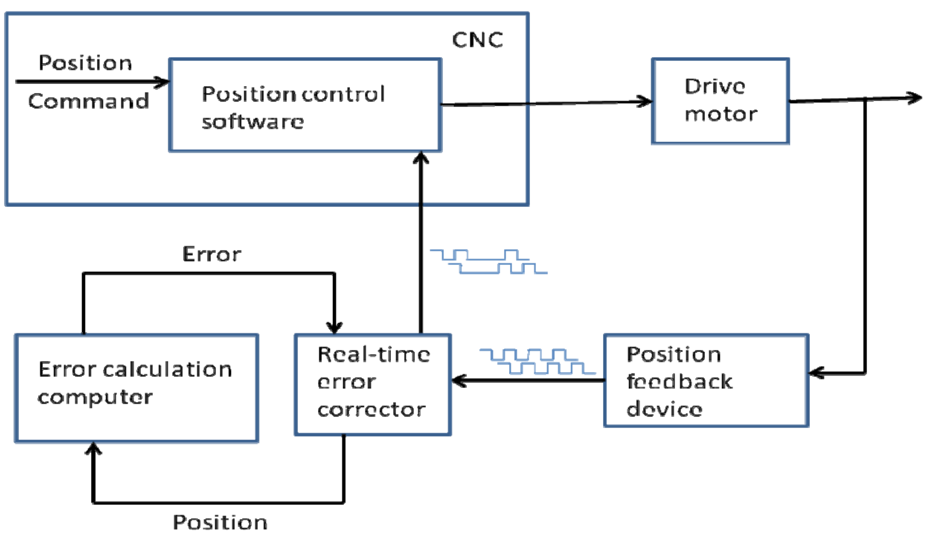
Recognizing the significant benefits of automation provided by numerical control in eliminating random procedures thus random behavior, in the last five decades, many researchers have focused on understanding the fundamental deterministic behavior of error motions of machine tools caused by the geometric and thermal influences such that they can be compensated by numerical control functions [20, 21, 22]. With the advances of robotics research in the 1980s, the kinematic modeling of moving structures using the homogeneous transformation matrices had become powerful tools for programming and controlling robotic devices [23]. Following these developments and assuming rigid body motions, a general methodology for modeling geometric machine tool errors was introduced using the homogeneous transformation matrices to define the relationships between individual error motions and the resulting position and orientation of cutting tool with respect to the workpiece [24]. The kinematic models were further improved to describe the influences of the thermally-induced error components of machine tool motions [25, 26].

1.5.7.4 Correcting machine errors

Automation of machine tool operation by computer numerical control and the modeling of machine tool systematic errors led to the creation of new hardware and software error compensation technologies enabling improvement of machine tool performance. Machine error compensation in the form of leadscrew pitch errors has been available since the early implementations of CNC. Such leadscrew error compensation is carried out using error tables in the machine controller. When executing motion commands, the controller accesses these tables to adjust target positions used in motion servo algorithms (feedforward control). The leadscrew error compensation tables, therefore, provide one-dimensional error compensation. Modern machine controllers have more sophisticated compensation tables enabling two- or three-dimensional error compensation based on pre-process measurement of error motions. For more general error compensation capabilities, researchers have developed other means of interfacing with the controllers. One approach for such an interface was through hardware modification of the communication between the controller and the position feedback devices [27]. In this case, the position feedback signals are diverted to an external microcomputer, where they are counted to determine the instantaneous positions of the slides, and corresponding corrections were introduced by modifying the feedback signals before they are read by the machine controller. Similarly, the software approaches to error compensation were also implemented by interfacing with the CNC through the controller executive software and regular Input/Output (I/O) devices (such as parallel I/O) [28]. The generic functional diagrams depicting the two approaches are shown in Figures 2a and 2b.



a) Software-based error compensation



b) Hardware-based error compensation

Figure 2 – Hardware and software error compensation approaches

The real-time error compensation of geometric and thermally-induced errors utilizing automated features of machine controllers have thus been reported in the literature to improve the precision of machine tools by up to an order of magnitude. Today's commercially available CNCs employ some of these technologies and cost-effectively transfer these benefits to the manufacturing end users.

1.5.7.5 Closed-loop machining (automation enabled precision)

Beyond just machine tool control through CNC, automation made significant inroads in manufacturing operations over the last several decades. From automated inspection using dedicated measuring systems such as go/no-go gauges situated next to the production equipment to more flexible and general purpose inspection systems such as coordinate measuring machines have improved the quality control of manufacturing processes thereby enabling more precise production.

Automation has even changed to paradigm of traditional quality control functions. Traditionally, the function of quality control in manufacturing has been the prevention of defective products to be shipped to the customers. Automation of machining, machine error correction and part inspection processes have led to the new quality control strategies where real-time control of processes is possible based on real-time information about the machining process and equipment and the resulting part geometries.

In the mid 1990s, the Manufacturing Engineering Laboratory of the National Institute of Standards and Technology demonstrated such an approach in a research project called "Quality In Automation" [29]. A quality-control architecture was developed that consisted of three control loops around the machining process: real-time, process-intermittent, and post-process control loops (see Figure 3).

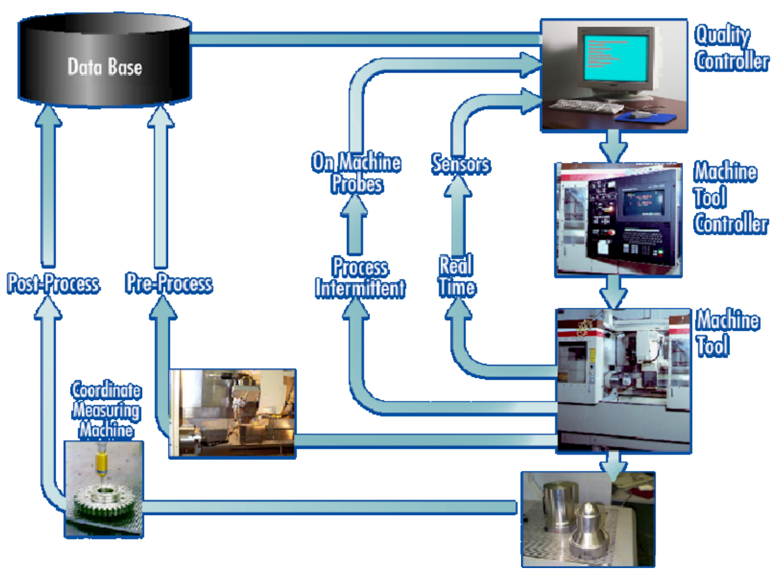


Figure 3 - A multi-layered quality-control architecture for implementing closed-loop machining

The function of the real-time control loop was to monitor the machine tool and the machining process and to modify the cutting tool path, feed rate, and spindle speed in real-time (based on models developed ahead of time) to achieve higher workpiece precision. The function of the process-intermittent control loop was to determine the workpiece errors caused by the machining process, such as the errors caused by tool deflection during machining, and to correct them by automatically generating a modified NC program for finishing cuts. Finally, the post-process control loop was used to validate that the machining process in under control and to tune the other two control loops by detecting and correcting the residual systematic errors in the machining system.

1.5.7.6 Smart machining

Enabled by automation, the latest developments in machining are leading the technology towards the realization of autonomous, smart machining systems. As described in the previous paragraphs above, the continuous improvements in machining systems through the NC and the CNC as well as the implementations of various sensing and control technologies have responded the continuous needs towards higher precision products at lower costs. However, machining systems still require relatively long periods of trial and error process to optimally produce a given new product. Machine tools still operate with NC programs, which provide the design intent of a product to be machined only partially at best. They have no information about the characteristics of the material to be machined. They require costly periodic maintenance to avoid unexpected breakdowns. These deficiencies increase the cost and time-to-market, and reduce the productivity.

The smart machining systems are envisioned to be capable of self recognition, monitoring and communication of their capabilities; self optimizing their operations and self assessing the quality of their own work; and self learning for performance improvements over time [30]. The underlying technologies are currently being developed by various research and development organizations. For example, a robust optimizer developed at the National Institute of Standards and Technology demonstrated a way to integrate machine tool performance information and the process models with their associated uncertainties to determine the optimum operating conditions to achieve a particular set of objectives related to product precision, cycle time and cost [31, 32, 33]. New set of standards are being developed to define the data formats to communicate machine performance information and other machine characteristics [34, 35]. New methods to determine material properties under machining conditions (high strain rates and high temperatures were developed to improve the machining models that are used in machining optimization [36]. New signal processing algorithms are developed to monitor the condition of machine spindles and predict failures before catastrophic breakdowns. It is expected that in the next five to ten years smart machining systems will be available in the market place providing the manufacturers cost-effective means of achieving high-precision products reliably.

1.5.8 Conclusions and future trends

Automation is a key enabler to achieve cost-effective, high-quality products and services to drive the society's economical engine. The special duality relationship between the automation and precision (each driving the other) escalate the effectiveness of automation in many fields. In this chapter this relationship was described from a relatively narrow perspective of discrete part fabrication. Tighter tolerances in product components that lead to high-quality products are only possible by high degree of automation of the manufacturing processes. That is one of the reasons for the drive towards more manufacturing automation even in countries with low labor costs. The examples provided in this chapter can easily be extended to other economic and technological fields demonstrating the significant effects of automation.

The recent trends and competitive pressures indicate that more knowledge has been generated about the processes, which leads to the reduction of apparent non-systematic variations. With increased knowledge and technical capabilities, the producers are developing more complex, high-value products with smaller number of components and subassemblies. This trend leads to even more automation with less cost.

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