SENSOR-BASED REAL-TIME ERROR COMPENSATION

Frederick Proctor
National Institute of
Standards and Technology
Gaithersburg, Maryland

ABSTRACT

Machining accuracy can be greatly increased through the use of high-resolution position sensors, calibration of machine tool or robot components, and other measures which serve to improve the machine’s positional response to part programs. Unfortunately, much of the inaccuracy in finished parts is due to dynamically varying quantities, such as tool wear, chatter, or thermal expansion; random errors such as part misplacement or dimensional tolerancing; errors in the geometric models of the machine; and errors such as backlash, gear eccentricity, and slide nonlinearity. Methods have been developed which rely on sensors to measure these quantities in real time as the part is being machined, and modify the position of the machine tool or robot accordingly. Improvements in absolute accuracy by a factor of twenty have been demonstrated on machine tools. A limit to implementing these methods is in the ability of machine tool and robot controllers to accept real-time sensor feedback.

INTRODUCTION

Automating the manufacturing process has long been touted as a means to improve throughput and improve quality. Typically, factory automators relied on machine tools and robots to replace workers in processes which were labor-intensive or error-prone. However, by replacing humans with machines, the ability to adapt to uncertainties or recover from unexpected errors was lost. This problem was solved by the addition of support equipment, or the modification of assembly line tasks such as part handling, which made previously unpredictable manufacturing steps repeatable to insure that intelligent adaptation was no longer required. When automation proceeded in this manner, factories were able to produce higher quality products with a substantially lower labor cost.

However, imposing strict measures to obviate the requirement for adaptation does not work for all applications. This is particularly true for precision machining. For example, errors due to the thermal expansion of a machine tool or to the wear in the cutter may exceed the tolerances for the part. To some degree, thermal errors may be compensated for by long warm-up cycles, which cost time and therefore money; or by designing the machine tool out of materials which do not appreciably deform in the presence of heat, which may be prohibitively expensive or even impossible. Tool wear may be accommodated with frequent tool changes, which is again costly, or by using extremely hard (and costly) cutters which do not wear appreciably. All of these solutions add cost to the machining process. What is desirable is to have some means of measuring the deviation of the machine tool, robot, or cutter from its assumed geometry, so that the amount of expansion or wear can be factored in to its control. While this ability to measure and adapt adds complexity and cost to any manufacturing system, it has proven to be feasible using current modest technology, and has demonstrated improvements in machining accuracy by an order of magnitude.

At the National Institute of Standards and Technology, engineers have developed several systems which make use of sensor information at various stages in the machining process, in order to improve accuracy and surface finish. These applications span the domains of machine tool and robot control. In particular, this paper will address three levels of machine tool control: thermal compensation in real-time, using temperature measurements and models of machine tool geometry; fast probing on machine tools to measure the effects of tool wear for process-intermittent control; and coordinate measuring machine characterization of finished parts for quality control and model verification. Additionally, this paper will discuss a robotic chamfering application which relies on force measurements at high frequencies to maintain a precise chamfer depth in the presence of robot inaccuracies, part misplacement, and tolerance uncertainties.

MACHINE TOOL ERROR COMPENSATION

The precision of machined part dimensions depends upon the accuracy of the position of the machine tool's cutting edge relative to the part. This accuracy is affected primarily by the geometric errors of the machine tool, such as backlash in gearing and non-linearity in slides, and by the non-uniform thermal expansion of the machine tool and parts themselves. Static calibration can significantly reduce geometric errors, but its effectiveness is reduced when thermal expansion deforms the components which have been calibrated. Because such heating occurs in localized hot spots, the resulting effect on the geometry of the machine tool is complex. To improve the accuracy of a machine tool, it is sensible to focus on reducing the combined effects of geometric and thermal errors. Furthermore, if such effects can be minimized, an increase in throughput would be realized due to the removal of the requirement for a warm-up cycle[1].

Researchers in the Automated Production Technology Division of the National Institute of Standards and Technology have developed a three-level approach to machine tool accuracy enhancement, as part of a Quality in Automation (QIA) program[2]. The foundation of the QIA program is a control architecture which features three sensor-based controllers which operate at decreasing cycle times: a real-time control loop, a process-intermittent control loop which relies on fast probing, and a post-process control loop using dimensional information generated by a coordinate measuring machine. The QIA architecture has been implemented on both a vertical machining center and a turning machine.

Real-time Control

The real-time control loop of the QIA architecture monitors the machining process as it occurs, measuring quantities which can be used to compute errors and modifying either tool path, feed rate, or spindle speed to reduce the effect of the errors on the part dimensions. Most of the research at this level has focused on thermal compensation techniques. In this method, a geometric-thermal model is developed which estimates the various components of a machine tool's systematic errors for given positions and temperature gradients. A kinematic model of the machine tool is also generated, which is used to compute how the errors in various components will affect the overall error in the tool tip position. The development of these models is analogous to calibration, which need be done only once and is used continually thereafter. The machine tool is instrumented with temperature sensors which are monitored by a host computer, which computes tool tip errors based on the geometric-thermal model and the kinematic model. Practical difficulties arise when attempting to feed this information back into the machine tool controller, since most controllers do not provide access to the servo controllers which easily support such feedback.

Typically, three approaches may be used to apply computed error compensation to a machine tool. One is to inject the error compensation signal directly into the servo control hardware as an analog voltage. This method was applied to the real-time error compensation of a Brown and Sharpe* vertical machining center at NIST. The technique is suitable for controllers which implement servo control using hardware, but in many systems servo algorithms are computed in software or firmware, and the injection of an analog signal is inappropriate. In these cases, the compensation signals are represented digitally, and are input to the controller via ports and written to registers that are read during the servo computations, such as the registers which contain the following errors. At NIST, this second method has been applied to the enhancement of a Hardinge turning center[3].
Alternatively, one can insert a real-time error corrector (RTEC) between the position feedback element of the axes of the machine tool and the machine tool controller[4]. This device independently counts the unaltered signals from the feedback element, and alters the signals before they are provided to the machine tool controller. The value of the alteration depends upon calculations made in real time based on models of the machine tool and sensor measurements. At NIST, this third method has been applied to a Monarch Metalist turning center, with thermal feedback.

The advantage of these methods is that such error correction is transparent to the higher levels of the controller; that is, the part programmer or the machinist overseeing operations are not responsible for any additional tasks, and are unaware of the presence of the compensation (except, of course, for the improvement in performance).

Test results of thermal compensation on the Hardinge turning center demonstrated significant improvements in the accuracy in diameter, length, taper, and squareness for a cylinder fabricated from mild steel[3]. For example, for a nominal diameter of 41 millimeters, the uncompensated machine tool generated an oversize of 57 micrometers, while the compensated machine tool improved to an undersize of 3.8 micrometers, an improvement of almost 15 times. The improvement in length was more pronounced: for a nominal length of 87 millimeters, the uncompensated length was oversized by 130 micrometers, while the compensated length improved to an undersized 6.3 micrometers, a factor of almost 21 times.

Process-intermittent Control

While the real-time error compensation techniques discussed above are successful in reducing the effects of thermally-induced errors, errors such as varying tool length, tool wear, and deflection will not be compensated. To address problems of this type, a higher-level process-intermittent control loop has been developed which uses part probing on the machine tool to

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* Certain commercial equipment is identified in this paper in order to adequately specify the experimental procedures. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the equipment specified is necessarily the best for the purpose.

determine the errors introduced on the machined part dimensions. Depending upon the complexity of the measured errors, the tool offsets or the NC programs are modified, or the error is corrected in real time along with the geometric-thermal errors.

Part probing on a machine tool is a time-consuming process. Using the built-in probing capabilities of machine tools, feed rates of about 120 millimeters per minute are the norm. When used for indicating the newly-fixtured part into the machine tool, these feed rates are acceptable. However, probing for process-intermittent control, particularly to determine form error, requires significantly more points than for indicating, resulting in a potential productivity reduction. To reduce the probing time, fast probing techniques have been developed which increase the feed rates to approximately 2500 millimeters per minute, using NC programs which do not place the machine tool controller into its native probing mode[5].

In order to perform probing at these increased feed rates, it is crucial to characterize such parameters as the time delay between the probe trip and the output signal, the tip diameter, the probe trip force, and the pretravel, so that these effects can be removed and accurate measurements of part dimensions can be made. Furthermore, it is important to insure that the probe will trigger during the constant-velocity portion of the feed, to maximize repeatability. Once these measurements have been made and probing profiles generated, probing can proceed at dramatically increased rates. In tests on a Monarch Metalist lathe using a General Electric Mark Century 2000 controller, six points were probed in 11 seconds, 3 times faster than conventional probing[5].

The task now is to use the collected probe data to improve the accuracy during subsequent machining passes. Tool offsets may be adjusted easily, if the probing data shows that the part errors are the result of tool wear. In more complex situations, such as errors in plane angle or deformed shapes, the actual tool path values in the NC programs need modification. When this is the case, the coordinates must be modified so that the original smooth shape of the feature is preserved. This is accomplished performing a least-squares fit of the modifications to a polynomial whose degree is sufficient to represent the features, which may be lines, circles, and quadratic or cubic curves. Alternatively, the form errors can be corrected using a real-time error corrector.

Post-process Control

In the QIA architecture, post-process control is used to verify the cutting process, and to tune the lower control loops by detecting residual errors. Post-process control is based on the use of a coordinate measuring machine (CMM), which inspects parts independently of the machine tool. Errors measured by the CMM can be used to modify the geometric-thermal and kinematic models used during real-time control, or to change the algorithms used by the process-intermittent control loop.

The notion of a control loop becomes blurred at the cycle times typical of the higher levels of the QIA architecture. The time between CMM data acquisition, data analysis, determination of modifications required at the lower-level control loops, and their implementation may be on the order of days or weeks. In fact, since the results of a sensing operation (the highly accurate CMM position measurement) is used to modify the characteristics of the controllers, the post-process control loop is actually a form of adaptive control, albeit aided by the analysis of human experts. With the adoption of data standards for computer-aided design (CAD) software, machine tools, and coordinate measuring machines, portable systems in which there exists no requirement for human experts at any level can be developed. Two of the goals of the QIA post-process control project address this possibility: an acceptance of standards which will allow CAD and CMM programs to share data; and the integration of the entire inspection process into a single system. The former removes the need for a human operator to perform the tedious tasks of translating and transferring data and programs from one platform to another. The latter allows post-process control techniques to be transferred to industry users, improving inspection capabilities and product quality.

Two data standards have been identified which will allow CAD and CMM programs to share data. The Initial Graphics Exchange Specification (IGES) defines a common data format in which part geometry can be represented[6]. IGES has been adopted by several CAD software companies. A second standard, the Dimensional Metrology Interface Specification (DMIS) adopted by the American National Standards Institute (ANSI) in February 1990, prescribes a common language that will allow CMMs and CAD packages from different vendors to share programs and data[7].

An integrated CMM controller has been developed which runs on a single PC-compatible computer, which integrates the entire inspection process into a single system. This system accepts part geometry data in IGES format, generated by the CADKey commercial software package. Inspection paths formerly generated manually, using a combination of teaching and text programming, are instead generated graphically by a user who manipulates the CMM probe in animation, selecting the inspection points and other pertinent information. The inspection paths may be verified in animation, so that the user may preview the probe motion and identify any errors. The CMM on which the post-process inspection is performed is a Sheffield Apollo Cordax, which is controlled in its native language on a separate PC-bus card. The DMIS path resulting from the graphic programming session is converted to the proprietary Sheffield format by a translator, and loaded onto the auxiliary processor board for execution. The resulting inspection data is stored in each of two formats: the native format, and DMIS. The DMIS data is read into Qualstar, a commercial software package, and analysis proceeds on a point-by-point or feature-by-feature basis. Specifically, the as-is and to-be dimensions are compared and analyzed for trends that would indicate modifications to either the geometric-thermal and kinematic models of the real-time error compensation loop, or modifications to the probing algorithms which make up the process-intermittent loop.

A drawback of these methods as they have been applied to commercial controllers is the lack of standard interfaces which allow the input of feedback information at the servo level. This was the impetus to develop the real-time error corrector. The lack of standards has been particular vexing to NIST, which has been charged with the task of developing and transferring technology to domestic industries. While the performance improvements of real-time thermal error compensation, fast probing, and CMM verification have been successfully demonstrated, transferring this technology has been extremely difficult due to the specificity of the engineering details to particular proprietary interfaces. Usually, small- or medium-size shops do not have the technical staff available to make the necessary modifications to the software or hardware developed at NIST, even when these modifications are minor.

FORCE CONTROL FOR ROBOTIC CHAMFERING

Chamfering is a machining operation which forms slightly beveled faces on part edges, and is typically followed by a brushing or blending process to produce a final radius. Because chamfering is one of the final manufacturing steps, it is critical that it be performed reliably, since all the value added to a part will be lost if the part is scrapped. Curiously, chamfering is often performed manually, introducing an unpredictable human factor at a most critical stage. The reason for this is the common prevailing notion that minor flaws, such as burrs or poor surface finish, will be magically removed at the finishing stage. Because of this, a mixed bag of defects accumulates until only a human, with a capability to reason and adapt, is capable of performing the myriad of operations necessary to remove the defects. Unfortunately, with a human’s flexibility comes a tendency to make mistakes, grow bored or tired, or suffer from repetitive stress disorders. In order to improve the quality of chamfering, particularly precision chamfering on complex parts, it is highly desirable to automate it.

One approach to automating chamfering is to process the part on the machine tool immediately after cutting. This method has two advantages. First, there is no downtime incurred by transferring the part. Second, any systematic errors such as geometric inaccuracy and thermal expansion will be similar for both the machining and chamfering passes, so their effects will be masked. However, this approach is not always feasible. For example, a part produced on three-axis horizontal and vertical milling machines will in general contain edges that require five axes of position and orientation control to chamfer. In cases where five-axis milling machines are available, shop managers may find it hard to justify using them for chamfering when there is a backlog of complex machine jobs which cannot be completed any other way. Furthermore, the fine dust generated by chamfering may ruin normal machine tool seals, which are designed for much larger chips.

A second approach is to move the parts to a robotic workcell specialized for chamfering. Robots are normally chosen over dedicated part-specific automation systems because they may be reprogrammed to handle a changing inventory of parts. Moving parts to such a workcell presents its own problems. The most severe is in registration, where the location of the part edges is known only approximately due to tolerances, inaccuracy of the machine tool in the previous workcell, errors in fixturing, and kinematic and dynamic errors in the robot. The tolerance problem can be overcome by passing the particular choice of dimensions from one workcell to its successor. Machine tool accuracy, part fixturing errors, and robot kinematic and dynamic errors present more difficulty. One way to reduce their effects is to precisely measure the location of the edges, using probes or cameras in a mapping pass before chamfering. This method may also be extended to detect anomalies such as burrs. Alternatively, the position of the edges may be determined in real time, as the chamfering tool traverses the edges, using force feedback, acoustic emission, or vision information.

It is advantageous to generate robot coordinates based on part drawings or CAD files, as they are for machine tool coordinates, instead of using the method of teaching commonly employed in industry[8]. Teaching requires that the robot be brought off the production line, and it also requires a human programmer for each part to be finished. However, computed robot coordinates (like those of a machine tool) rely on the accuracy of the robot. Because the design of robots typically includes articulated joints with a large range of motion, their accuracy is severely limited, especially when compared with machine tools. Because of this, it is crucial that some means to accommodate for this inaccuracy be built in to the robot finishing workcell. Calibration of the kinematics is a first step, which can be improved with models of the backlash characteristics of the joints, or stiffness and inertia models which can predict dynamic quantities such as overshoot. Unfortunately, generating the data from which to develop these models is an exceedingly difficult task. In many cases, the use of proper sensory feedback provides a natural way to overcome the limits of robot accuracy, particularly when they stem from several unrelated or poorly-understood sources.

The Advanced Deburring and Chamfering System

Researchers at NIST and United Technologies Research Center are working jointly to develop an automated chamfering workcell, to be applied to the finishing of U. S. Navy aircraft engine components made from titanium and inconel metals[9]. This system is known as the Advanced Deburring and Chamfering System (ADACS). The strategy is to use a robot as a coarse positioning device, which carries an actively-compliant chamfering tool to the part edges. The robot is a Cincinnati Milacron T3-646 electric six-axis robot, with a payload of 70 kilograms. The chamfering tool consists of a carbide rotary file, a high-speed electric spindle, force transducers, and an actuated housing driven by stepper motors and lead screws. This tool, the ADT-1A, is controlled independently from the robot, and can be reprogrammed almost instantly to emulate a wide range of stiffness and damping in both the normal and tangential edges directions. Fine motion capabilities allow the tool to track edges based on force feedback, so that edge contours can be traversed and precise chamfer depths maintained in spite of robot inaccuracies, deviations in part geometry, and fixturing errors. This strategy is known as the around-the-arm solution, in contrast to the through-the-arm solution in which the robot itself is given frequent position updates in response to force feedback. The around-the-arm solution has proven to be a more effective method, primarily because robot controller delays, joint backlash, and link inertia limit the control bandwidth to be far below that required to maintain a consistent chamfer depth without breaking into oscillations or limit cycles[10].

Measurement Tasks

Experience with chamfering in the ADACS have shown that the current design of the ADT-1A is insufficient to overcome robot inaccuracies and produce chamfers within the tolerances required by engine manufacturers. Two recent suites of tests performed at United Technologies Research Center and at NIST have generated a set of requirements for the capabilities of an improved robotic chamfering system. The test were formulated so that a second-generation chamfering tool could be developed which would handle the types of kinematic and dynamic errors to be expected with a typical industrial robot.

For the first suite of tests, engineers at United Technologies Research Center, under contract to NIST and the Navy, ran an extensive series of chamfering test using carbide rotary files on inconel test coupons. The result was a model which relates normal cutting force to feed rate, rotational speed, chamfer depth, and material removed[11]. Additionally, values for the force resolution, accuracy, and range were determined. The force values for this application, in newtons, are 0.0090 for resolution, 0.072 for accuracy, and 0.00 to 18 for range. These figures serve as design parameters for a successor to the ADT-1Ato be used on Navy inconel aircraft engine components.

A second suite of tests performed on the robot was intended to characterize its point-to-point repeatability, accuracy, and dynamic path deviation for nominal chamfering trajectories. A laser tracker system was used to determine these values. With this system, a laser beam is directed onto a reflective target, which is precisely constructed so that incoming and outgoing beams are parallel. The laser tracker itself is servo controlled, and will adjust the outgoing beam onto the optical center of the reflector so that the outgoing and incoming beam are coincident. An interferometer in the tracker precisely measures the range of the optical center, while encoders measure the azimuth and altitude. The combined precision of the tracker system is approximately 20 micrometers.

The repeatability was determined as follows. First, a repertoire of points in the neighborhood of a typical chamfering position was selected. For each point, a path was constructed which ended on the point and caused significant motion for each robot joint. A series of approximately one thousand paths were executed in sequence, beginning at cold power-on and terminating well after thermal equilibrium was reached several hours later. The resulting data consisted of a set of roughly coincident points whose standard deviation gives a measure of the repeatability. Since the tests included the warmup cycle, the thermal expansion of the robot was apparent, although plans at this time do not include correlating thermal measurements with robot geometry. From this analysis, the repeatability of the robot after thermal equilibrium was attained was determined to be approximately 0.70 millimeters. This figure is actually a composite of the repeatability in three axes, since the points define an ellipsoid with a pronounced major axis and two minor axes. The pronounced major axes coincided with the degree of freedom associated with the first base joint of the robot, whose backlash contributes the most to the repeatability error due to its distance from the tool tip and the large backlash due to its design.

The 0.70 millimeter repeatability figure for the robot is not the limiting factor when determining the effect of robot errors on tool tip position resulting from off-line programs. More significant is the accuracy, whose relevant aspects can be obtained by acquiring data along a nominal straight path. Laser tracker tests on commanded straight-line trajectories in each of the robot’s three Cartesian coordinate axes show deviations from true orthogonality and linearity. Data reduction techniques can be applied to this data to determine the position and orientation of the best-fit origin; that is, the coordinate frame which minimizes the measured least-squares deviations of measured paths from commanded paths. When this origin was determined, the magnitude of the non-linearities (a measure of the accuracy) was computed to be approximately 7.2 millimeters. This figure is an order of magnitude greater than the measured repeatability, which is typical for industrial robots. This value determines the magnitude of the fine-motion capability of a chamfering tool which is required to compensate for inaccuracy. In actuality, the fine motion must be twice this to accommodate for errors within this radius, and must practically be larger since the accuracy figure is a least-squares measure, and worst-case errors may be once again as bad. If this assumption is made, the diameter of the fine motion capability of the chamfering tool should be approximately 3 centimeters. Of course, the results of the accuracy tests can easily be used to develop calibrate the robot about neighborhoods of interest, so this figure represents a worst-case design parameter to be used in the absence of any calibration. The accuracy tests performed as described above measure the static accuracy; that is, the accuracy of a slowly-moving robot without dynamic effects such as overshoot. To characterize the dynamic effects, laser tracker data was gathered while the robot followed two types of trajectories at various feed rates.

The first dynamics test, known as a cone test, required that the robot undergo purely rotational motion while keeping the tool center point at a fixed location, effecting a cone. For a robot whose wrist axes intersect at a point offset from the tool center point (like the T3), this type of test often indicates large errors. These errors are due to the large motion required of all robot joints to effect pure rotation about an unnatural point. In contrast, robots whose wrist axes intersect a the tool center point need only move two or three wrist joints to effect the same orientation changes, resulting in far less position deviation. For the NIST T3 robot, laser tracker data was gathered for cone traversal times between 8 and 60 seconds. The results indicated large tool tip deviation, as expected. For example, at the slowest speed, the tool tip wandered roughly in an ellipse whose major axis measured 5.0 millimeters and whose minor axis measured 3.2 millimeters. At the fastest traversal time of 8 seconds, the dynamics increased the deviation to an ellipse which measured 25 millimeters by 10 millimeters. These dynamics are very difficult to counteract, and are best avoided by designing a tool mounting which allows the desired 45-degree chamfer angles to be produced with only wrist axis motion. Preliminary results showed that the dynamics in this case resulted in an ellipsoid whose dimensions were approximately 2.0 by 2.0 millimeters. When this is done, the remaining wrist dynamics can be accommodated by a force feedback loop which maintains cutter contact.

The second dynamics test required that the robot maintain a constant orientation, and undergo pure translation along a series of rectangular segments in a plane. Since the joint motion required for this test is much lower than for conical motion, the deviations measured during these test paths were correspondingly smaller. For a typical feed rate of 500 millimeters per minute, the maximum path deviation (due to overshoot at corners) was approximately 3.2 millimeters, far less than for pure orientation.

These tests have resulted in the preliminary specifications for a force-controlled chamfering tool capable of processing inconel metal parts with geometries typical of aircraft turbine engine components. Based on the requirements for chamfer depths, chamfer angles, and tolerances, the tool controller bandwidth, stiffness, and slew rate required to compensate for robot path inaccuracies has been determined. Simulations of the chamfer depth, using a typical cutter and robot position deviations identical to those measured for the T3, have indicated that these design parameters will produce the precision chamfers required by aircraft engine manufacturers in an automated system of this type[12].

SUMMARY

The use of position feedback has traditionally been used to guide machine tool and robot axes accurately toward their destinations. This feedback may take the form of angular signals output by resolvers and encoders, or linear signals generated by glass slides. In any case, the control of tool position further relies on a kinematic model of the device so that the position signals from the sensors may be used to compute the position and orientation of the tool tip. Inaccuracy results from both imperfect sensors and imperfect models of the machine. Furthermore, these imperfections may be nonlinear, or drift and change with time, making their prediction difficult. Incorporating sensors to aid in the prediction of these imperfections, or to perform more appropriate measurements, greatly improves the accuracy. These sensors include thermocouples which measure temperature gradients, or force transducers which measure machining force directly. The use of thermocouples in conjunction with geometric models to predict the actual geometry of machine tools has been demonstrated to improve machining accuracy by a factor of 20, and carries the additional benefit of allowing machining during warmup cycles. Force feedback for robotic chamfering operations allows precision chamfers to be generated in spite of part tolerances, fixturing errors, and robot position inaccuracy, which are quite pronounced when robot paths are generated by off-line programming. Using force feedback, 0.30 millimeter chamfers have been precisely machined on inconel parts, in the presence of robot position inaccuracy of approximately 7 millimeters.

Closing feedback loops at lower frequencies allows the refinement of real-time models and further improvement in quality. These feedback loops may take the form of fast on-machine probing to measure tool wear at frequencies of several minutes, or off-machine coordinate measuring machine verification at cycle times of hours or days. Unfortunately, the lack of standard interfaces is a major obstacle to transferring this quality control technology to industry, especially to small- and medium-sized shops which cannot afford to dedicate engineers to modify NIST-developed software or interfaces to match the proprietary interfaces on their equipment.

Recently, with the advent of open architectures for computing systems, steps have been taken to define standard interfaces for controllers. This is the focus of the Next Generation Controller project, sponsored by the U. S. Air Force MANTECH program[13, 14]. It is hoped that controls builders, machine tool and robot vendors, and manufacturing software developers will begin to provide such standard interfaces, so that integrating products from different vendors is straightforward, and enhancements to commercial products will be portable.

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