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ENABLING MACHINING VISION USING STEP-NC

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ABSTRACT
STEP-NC is a new data format for manufacturing control. Part of the ISO 10103 Standard for the Exchange of Product Model Information (STEP) suite, STEP-NC covers numerical control (NC) of machine tools. One of its applications is to enable integrated on-machine measurement of machining processes using vision systems and other sensors. In this paper we describe the manufacturing process and manufacturing resource models in STEP-NC that can be used to enable this type of measurement. These descriptions include the machine setup so that the configuration of the part can be identified and corrected, the machine kinematics so that the actions of a machine while adding or subtracting material can be verified, and the product tolerances so that the quality of the final part can be predicted and corrected during the machining.

INTRODUCTION
To reliably and safely meet design tolerances, manufacturing has a highly disciplined culture that minimizes mistakes. It is very different than the culture of computer programming where an informal trial-and-error approach enables continuous innovation.

Part of the issue for manufacturing programming is that industry has been using the same vector-based languages for manufacturing control for more than forty years (see Figure 1). The discipline applied to the use of these languages is superb with Product Data Management (PDM), Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM) and Computer-Numerical Control (CNC) systems each managing their part of the problem, but like an assembly language, a vector language is very difficult to manage.

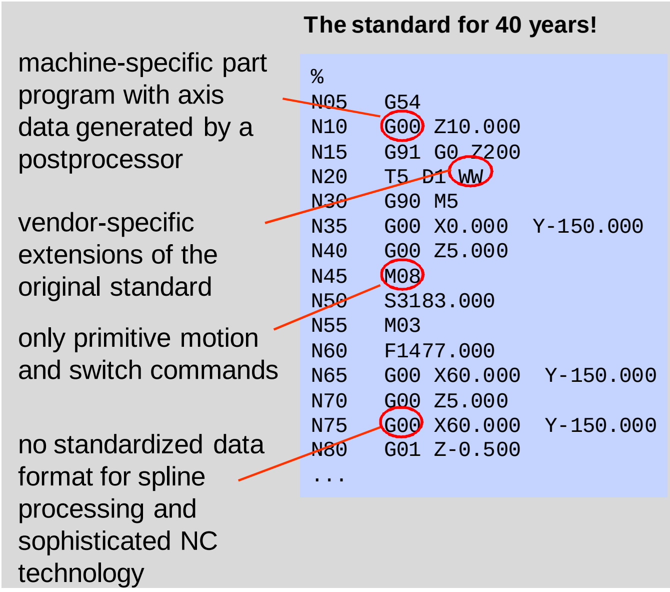

FIGURE 1 – Vector-based control codes

STEP Manufacturing is an ISO team that is developing a next generation language for CNC control. The new language enables the implementation of a new layer for CNCs that links the control to independent sensor systems (See Figure 2). Therefore, applications can be written to compare the in-process state of a part with the model predicted by a planning system and deviations between the two can be used to prevent errors and increase accuracy.

The new ISO STEP-NC language makes machining more effective by linking product models to process models and resource models (ISO 10303-238, 2007). The programs include CAD Geometric Dimensioning and Tolerancing (GD&T) data to enable on-machine verification and CAM process data to enable on-machine optimization.

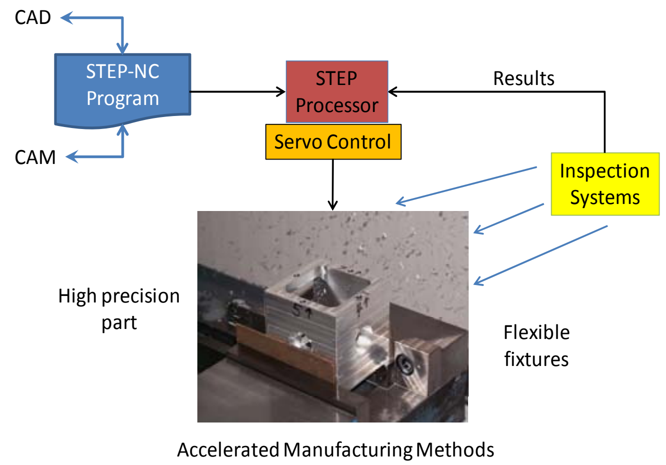

FIGURE 2 – Vision-based control

A machining workingstep in a STEP-NC program applies an operation to a feature using a cutting tool. The operations can be described as primitive tool paths or as sets of parameters that can be modified by intelligent processes. Figure 3 shows a STEP-NC program being simulated using software developed by STEP Tools, Inc.

STEP-NC is being tested in an international forum called STEP-Manufacturing by a team from industry, government, and academia. Over the past ten years, this group has exercised aspects of the standard to show faster art-to-part with feature recognition, interoperability across CAM and CNC, closed loop machining, automated feed-speed optimization, tool wear modeling, and machine tool modeling.

This paper describes the capabilities supported by STEP-NC for vision and inspection. The next section summarizes how machining processes are represented in the STEP-NC standard. The third section describes the features of the new model that can be used for inspection and vision applications. The final section contains some concluding remarks.

MODELING AND TESTING

STEP-NC is a machine neutral format for representing manufacturing operations and results (Nassehi et al 2007). It uses product geometry defined by STEP (ISO 10303 1994) and can define geometry for the workpiece at various stages in the process, the cutting tools, fixtures, and machine tool.

In STEP-NC, manufacturing operations are organized into workplans that contain workingsteps (Weck *et al.* 2003). Each workingstep performs an operation such as rough milling a pocket (Xu et al. 2005). The operation is applied to a feature that can be described parametrically and as a material removal volume. The operation may also be described as a set of parameters, or as a tool path to be executed by a set of resources. The high level descriptions make the machining program more resource independent, but require more processing. The low level descriptions are fixed to specific resources that must be available on the machine but allow for more specific error checking.

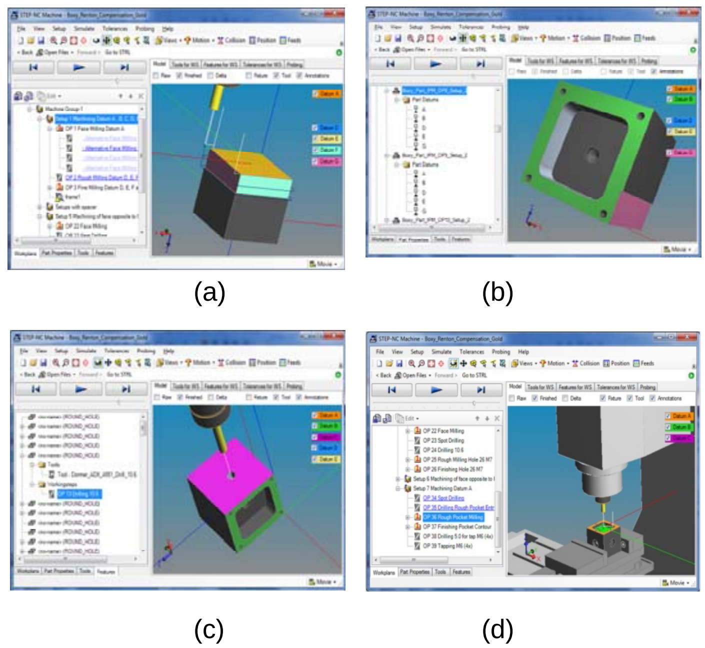

FIGURE 3 – Machining using STEP-NC. (a) workingsteps add or remove data volumes, (b) product models define geometric dimension and tolerance constraints, (c) manufacturing features with associated cutting tools, and (d) fixtures in setups on machine tool models.

Execution of a STEP-NC workingstep can be made conditional on the results of geometry measurements. All geometry in STEP-NC can be annotated with semantic Geometric Dimensions and Tolerances (GD&T) and inspection operations can be defined to validate these specifications at various stages of the manufacturing. The GD&T data is a new feature of the STEP translators in CAD systems. Advanced CAD systems such as Catia and NX are writing increasing amounts of this data with each new version of their systems and the other CAD translators are beginning to follow.

STEP-NC has been extensively tested by a team from industry, government, and academia. Table 1 lists a ten year history of the testing which can be divided into five periods. In the first period, the emphasis was on faster art-to-part using feature recognition. In the second period, CAM to CNC interoperability was shown by sending STEP-NC data from four different CAM systems to two CNC controls, where it was used verbatim to drive both tool-tilt and table-tilt machine configurations. The third period tested closed loop machining by including data to both machine and measure a part in a STEP-NC file. The fourth period worked on automated feed-speed optimization with extensions proposed for modeling the cross section of the material volume removed by a tool path. The fifth period extended the fourth to include tool wear modeling and performed the first machine tool modeling (Hardwick et al 2011).

Period	Capabilities shown	Purpose
Nov 2000 Feb 2002 Jan 2003 Jun 2003	Tool path generation from manufacturing features	Faster art- to-part
Feb 2005	CAM to CNC data exchange without post processors	CNC interoperability
May 2005 Jun 2006 Jul 2007	Integration of STEP CAD GD&T data with CAM process data	Integrated machining and measurement
Dec 2007 Mar 2008 Oct 2008	Cutting tool modeling per ISO 13399; cutting cross- section modeling	Feed and speed optimization
May 2009 Sep 2009 Jun 2010	Tool wear modeling; machine modeling	Closed-loop manufacturing

Table 1 – History of STEP-NC testing

DATA FOR INSPECTION APPLICATIONS

The STEP and STEP-NC models have five data components useful for inspection and vision applications.

Geometry. The geometry of the part can be described as a solid model at the start of the process, at the end of the process, and at multiple stages during the process.

Dimensions and Tolerances. The part dimensions and tolerances that must be met at the different stages of the manufacturing process.

Setups, Fixtures, and Machines. The fixtures that will be used to hold the part and the orientation of the part within those fixtures, the placement of the fixture on the machine, and the machine kinematics.

Inspection Operations to test the part for conformance to the tolerances at any stage of the manufacturing.

Machine Accuracy to predict and correct the accuracy of the final part.

Geometry, Dimensions, and Tolerances

Rich product geometry models are required in order for the end user to fully understand the behavior of the machine. The possible representations for this geometry can be divided into approximate, boundary, and parametric.

Facets are a very popular kind of approximate representation. They are easy to implement because the system only has to implement one or two types of data structures and if they are generated in fine detail, they can give a very good visual representation of the product. Boundary representations capture the shape geometry of each element using the most appropriate mathematical description. Boundary representations are commonly used to represent the elements of manufacturing models because they are accurate and can be made complete so that applications can determine the difference between the inside and outside of a model.

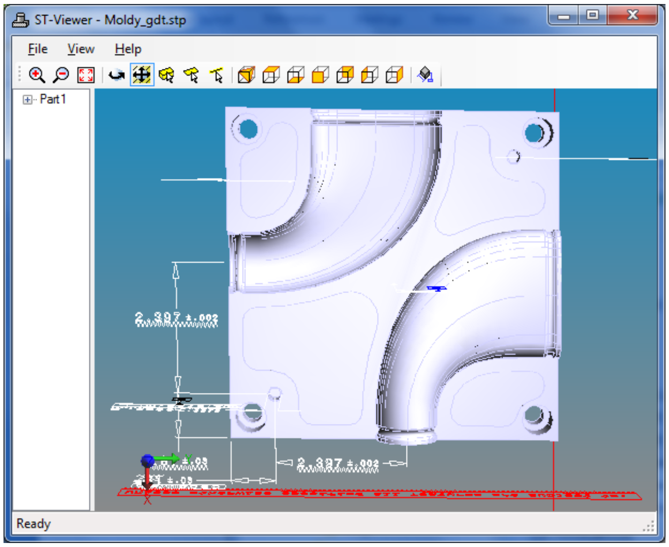

Figure 4 – Geometric dimensions and tolerances

Parametric representations are ideal for design because they make it easy to generate new designs for different product requirements. Parametric representations are not commonly used in machining because they are difficult to transfer between systems and because in most situations manufacturing is not allowed to change the design geometry.

Geometric dimensions and tolerances (GD&T) are a key requirement for manufacturing because no manufacturing process is completely accurate. Therefore, manufacturing needs to know when a result is good enough and this is defined using tolerances and other product manufacturing information (PMI). Traditionally, the required GD&T and PMI have been transmitted from design to manufacturing via drawings and the inherent ambiguity of this medium has inhibited automation (Zhao et al 2009). Example GD&T depictions are shown in Figure 4.

Setup, Fixtures, and Machine Kinematics

Many kinds of machine tools have been invented (Kjellberg 2009). Each machine gives its users a competitive advantage by allowing a particular type of operation to be performed more accurately or more quickly than its competitors. To achieve such advantages the designers of the machine work hard to give it the right geometry (mass), rigidity (materials), and kinematics (movements) for each operation.

STEP has a kinematics resource (ISO 10303-105) that has been included as one of the conformance classes in the AP-214 data exchange protocol. Figures 5 (a)-(c) show some of the machine tool kinematic configurations that have been verified during the STEP-NC testing (Li *et al.* 2011, STEP Tools 2012).

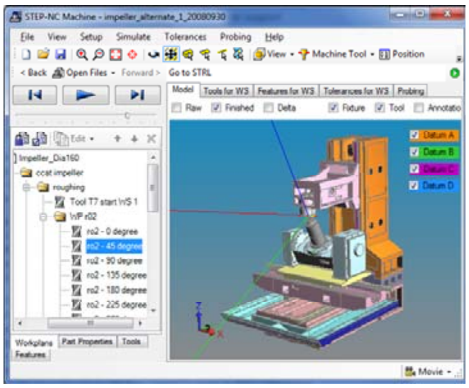

Figure 5 (a) – Five-axis trunnion

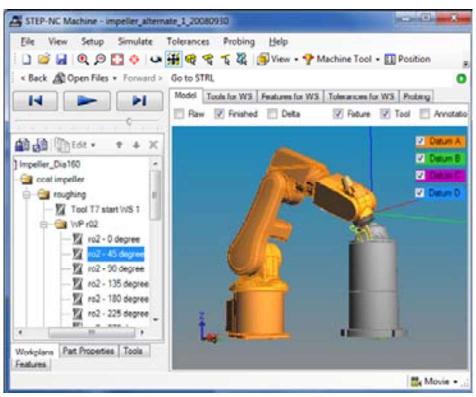

Figure 5 (b) – Six-axis robot

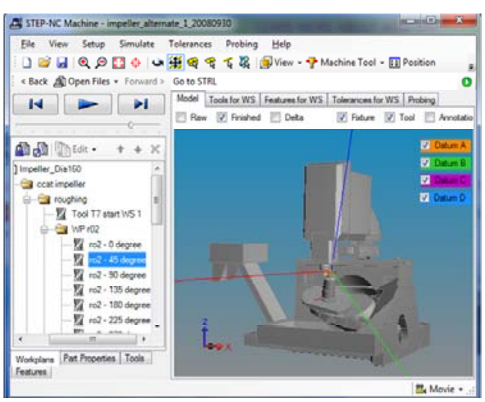

Figure 5 (c) – Five-axis nutating table

A STEP-NC program is divided into workplans containing workingsteps. Each workingstep describes how an operation is applied to a feature to achieve a result. The typical operation requires a machine head to follow a path in space. The path depends on the geometry of the resources being used on the machine and the design requirements on the path.

For a given set of tooling, a CAM planning system generates a path for the machine head that will result in the required material being removed or added to the part. These tool paths can be stored in the STEP-NC data along with the parameters of the operation and the geometries of the required design features. This aspect of the STEP-NC standard was tested during the international demonstrations (see Table 1).

The machine tool kinematics model describes how the components of the machine tool must move in order to execute the tool path given in the STEP-NC data. To date, the model has been tested on machines where there are two kinematic chains: one for the table holding the part and one for the machine or spindle head that is cutting the part or depositing material onto the part. Provided the mapping of the required movements is not mathematically ambiguous, the required transitions for each axis are computed and the machine tool runs the required program.

The machine tool kinematics are applied to a part that is held in a fixture. The fixture is located on the bed of the machine tool and the part is placed into the fixture. If the part is to be machined on multiple faces, then it may be setup multiple times.

The machine is connected to a part by a fixture. A part setup defines how the part is placed in the fixture and a fixture setup defines how the fixture is placed on the machine. Each setup uses a Homogeneous Transformation Matrix to map the coordinates of the part into the coordinates of the fixture and then into the coordinates of the machine.

The result is a part placed onto the machine as shown in Figure 5. A vision system can now check these coordinates and the behavior of the machine as it moves to execute the program. For example, if the first move of the program has been programmed to move the tool head ten units closer to the part, but because of an error in the physical setup, it moves ten units in the other direction, then an error condition can be signaled to the machine tool.

Inspection and Compensation Operations

Figure 6 shows a STEP-NC program that contains machining and probing operations. There are three datums on the part and the left of the figure shows details for the inspection workplan. Seven faces are to be tested using a touch probe. All of the paths for all of the tests are shown in the right part. Each face is highlighted. Algorithms in the software can compute the difference between the expected distance and the measured distance for each measurement point. Other algorithms can determine if the measurement points on the face are consistent with the face in question being in or out of the associated tolerance.

For example, the probe tool is shown at a point where it is about to touch the face of a cylinder that represents a round hole in the final part. This cylinder has two associated tolerances. A size tolerance defining acceptable dimensions for the hole diameter, and a perpendicularity tolerance defining the acceptable deviations for the hole axis.

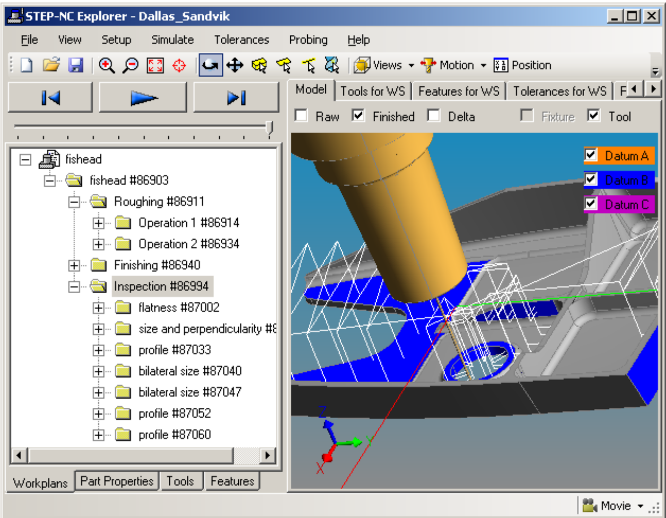

Figure 6 – Program measurements using a touch probe

Figure 7 gives another view of the tolerance data. In this figure the tolerances defined for the part are listed. The perpendicularity tolerance has been picked and the face associated with this tolerance (the round hole cylinder) is highlighted in light blue. In this figure the software lists all of the product models in the data and shows the tolerances defined for each model. For this program only the final part has tolerances, but any model in the STEP-NC program can be given tolerances, including the cutting tool models.

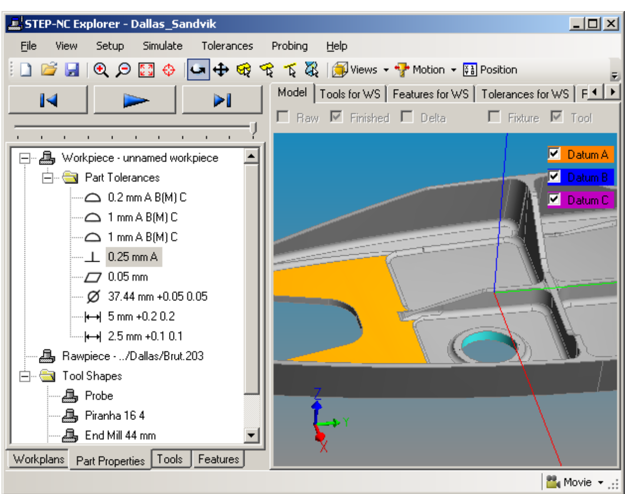

Figure 7 – Semantic tolerances

The tolerances shown in Figure 7 are called semantic tolerances because they are fully associated with the underlying geometry in the product model. The tolerances shown in Figure 4 are called presentation tolerances because they are drawn as labels in the computer graphics space. This is the method used to annotate drawings for more than a century, updated for 3D geometry.

The new STEP models support presentation tolerances and semantics tolerances so that the information can be understood by people (using the presentations) and by new applications (using the semantics) (Kramer 2010).

One interesting application for semantic tolerances is a new system to evaluate whether or not a program running on a machine tool can meet the tolerances required for its final part. If software can deduce that the forces on a cutting tool will cause a deflection sufficient to make the final cut out of tolerance, then industry will be able to evaluate the suitability of a machine for a process.

STEP-NC contains sufficient information to allow the forces on the cutting tool to be calculated and the STEP semantic tolerances allow an application to deduce if the displaced cut will cause the underlying surface to fail its surface profile tolerance. The missing piece of the puzzle is software to compute the size of the deflection from the forces. This requires more information about the rigidity and positional accuracy of the machine and this is discussed in the next section.

Machine Accuracy

Machining system capability links design to manufacturing by relating the geometrical and dimensional tolerances specified by the design to the accuracy and precision of the manufacturing equipment. Machining process results depend on both the variance and the aim of the process. A process with no variance will display a perfect precision.

Process capability is the long-term performance level of the process after it has been brought under statistical control. In other words, process capability is the range over which the natural variation of the process occurs as determined by the system of common causes.

While Quality Control studies check the product to determine whether or not it complies with what was specified by designer in the design, Process Capability studies are directed at the machine and processes used rather than the products from the processes. Hypothetically, if we could control the capability of machines and processes, then we can predict the outcomes from our machines and there will be no need to check products.

Process capability has three important aspects:

- design specification
- range or spread of variation
- centering of natural variation

Process capability models summarize the results of capability studies. These models are used to measure the producibility of new designs and to evaluate the performance of manufacturing processes. The process capability model is a transfer function that maps design and process descriptors into predictions of process variations.

Machine geometric errors are the basis for predicting machining accuracy and can be studied with two different methods: direct and indirect. Direct measurement detects errors of each machine element while indirect measurement detects the resulting total errors in a machining system. Direct measurement generally takes more time to carry out, but gives a detailed understanding of the error composition enabling reduction or compensation of the error at its source.

Indirect measurement generally takes less time to carry out and gives a detailed understanding of total geometric error in a machining system. These errors are dependent on both the static configuration of the machine and the dynamic errors caused by bending forces and energy dissipation. Schwenke et al. (Schwenke 2008) have classified them as follows:

- Kinematic errors;
- Loads;
- Dynamic forces;
- Thermo-mechanical errors;
- Motion control and control software.

Kinematic errors and loads are the primary factors in geometric error simulation. In the absence of kinetic energy and dynamic forces, they enable the prediction of machine movements. Geometric errors caused by loads are a result of elastic deformation in joints between the machine's elements, calculated as static stiffness (Hedlind 2011). Kinematic errors are determined by direct measurement. Load errors depend on the total static stiffness of the machine tool and can be determined from process-independent indirect measurements such as Loaded Double Ball Bar (LDBB) tests.

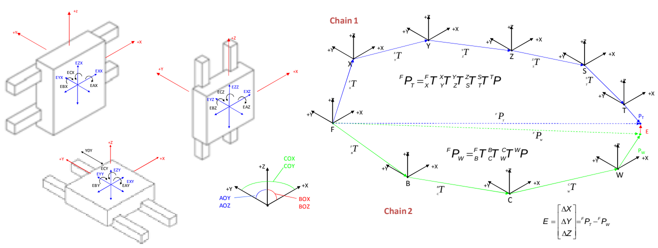

Figure 8 – Estimating machine tool static errors (kinematic and loads)

Each moving component causes both types of errors. LDBB tests can measure them at different locations. Two measurements are needed because different errors will occur for movements in the positive and negative directions. Interpolation can then be used to estimate errors for other positions and a total error for all the components can be accumulated as a series of Homogeneous Transformation Matrices (HTMs) as illustrated in Figure 8.

During machining simulation the surface normal of the part can be used to determine the cutting force vector component that has the most influence on the resulting geometry of the workpiece. The cutting tool force can be estimated from the volume of material being removed and the type of material. The deflection is calculated using the machine tool static stiffness and current joint positions. This deflection is added to the geometric error caused by the kinematic error in the joint positions.

Figure 9 shows an experimental apparatus used to measure the deflection of the machine tool under different force loadings. The design of the apparatus is based on the traditional double ball bar (DBB) measuring device together with a pneumatic cylinder to actuate the load. By combining the traditional DBB test and the capability to generate a load on the machine tool structure, more realistic conditions for accuracy measurements are created. For instance, the load can in some cases eliminate existing play in ball screws, play that under normal machining condition will be eliminated due to the effect of cutting forces on the structure.

The information computed from the capability models enables the information flow shown in Figure 10. As shown, the two types of static errors are measured to determine predicted tool paths for the manufacturing process on the measured machine tool. Provided the measured static errors dominate, a tolerance verification application determines the final geometry and dimensions of the manufactured part. In order that static errors shall dominate, the process planning function must create production plans that are within the manufacturing specifications with respect to spindle speed, material, and depth of cut.

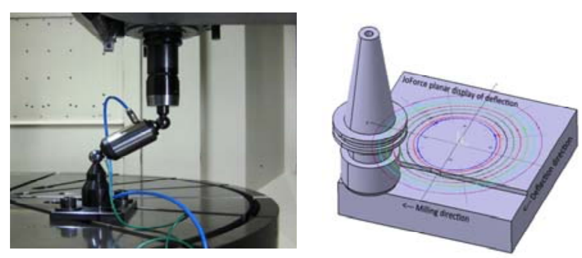

Figure 9 – Loaded double ball bar testing (left); machine static deflection as a function of applied load (right) (Archenti 2010)

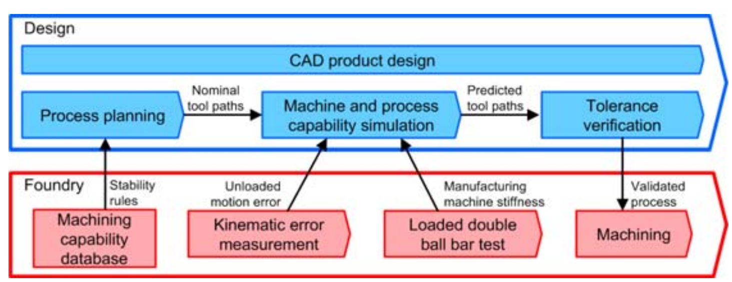

Figure 10 – Estimating process results

APPLICATION TO VISION

In this paper we have described what information is available in STEP-NC to enable integrated machining and measurement using vision systems and other sensors.

The sensors may range from the kinds of devices used on gaming systems such as the Microsoft Kinect (Microsoft 2012), to high precision robot mounted cameras.

In current experiments we are evaluating how they can be applied to the machining of a part called Boxy (STEP Tools 2011). There are many issues that need to be investigated including how to maximize precision and how to cope with the high reflectivity of many machined materials (most vision algorithms are degraded by specular reflection). However, in most cases these are issues for the wider vision community.

In the machining context STEP-NC gives us models of the as-planned machining system that can be compared against models detected using sensors on the "real" machine. Multiple commercial software systems are emerging that can compute geometric representations from images and point clouds of the "real" machine. Many of these systems deliver their results as STEP files. We are evaluating how to use those results in three scenarios (Hardwick 2010).

The first is a setup scenario similar to one previously implemented at Boeing using a commercially-available portable measuring arm (STEP Tools 2010). The arm was used to compute the coordinates of three planes. The data was delivered from the arm as a STEP file and the actual coordinates of the corner were used to adjust the setup. In a new experiment the coordinates of the three planes will be computed by vision software with the benefit of simpler operation.

The second scenario uses the product models to verify the setup. For this scenario we can use the vision system to determine if the components of the STEP-NC machining model correspond to the physical machine setup and if there are discrepancies to determine if they will interfere with the machining. An enhancement of this scenario measures the dynamic behavior of the machine during the machining to verify that the components are moving as predicted in the STEP-NC model. For example, in early design situations it is not uncommon for an operator to reverse signs or axes with the result that the cutting tool moves towards the part when it should be moving away or vice versa. A vision system should be able to detect such an error before it becomes serious.

The third scenario is the most ambitious. If the product model has tolerances, then the vision system can verify those tolerances. One approach is to use the STEP-NC tolerance data to inspect the part on the machine using a probe. A second more ambitious approach is to use the tolerance data to measure the accuracy of the machining cuts as they are executed and to adjust the parameters of those cuts in response to measured errors. The question that must be answered is how best to control manufacturing in such an environment.

The first scenario requires high precision but it is static because the machine tool will be stopped while the setup is being evaluated. Therefore, it may be ideal for a robot mounted camera. The second scenario only requires low precision, but it is dynamic because the machine tool is moving. It might be ideal for game-style devices perhaps supplemented by a robot mounted camera if the software determines that a new clearance will be tight. The third scenario requires both. Measuring a cut during machining is very dynamic and will require very high precision measurement. If this type of measurement can be managed, then many other manufacturing paradigms may be changed as well. An alternate less rigorous version of this scenario would be to do the measurement after the test cut is completed, in which case the measurement will be less dynamic.

CONCLUSION

The performance of high-resolution cameras and visual sensors is sufficient to measure many variables in manufacturing. The problem is the time and the effort needed to analyze the measurements and determine corrective actions. STEP-NC defines a rich environment for machining that should be able to considerably reduce this time and the next stage of our work is to quantify these reductions by performing experiments on the three scenarios.

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