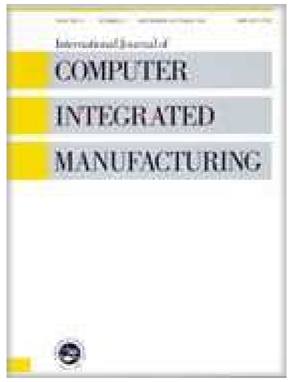
(Special Issue STEP-NC) Closed-loop CAPP/CAM/CNC process chain based on STEP and STEP-NC inspection tasks

C Brecher, Mirco Vitr, Jochen Wolf



(Special Issue STEP-NC) Closed-loop CAPP/CAM/CNC process chain based on STEP and STEP-NC inspection tasks

Journal:	*International Journal of Computer Integrated Manufacturing*
Manuscript ID:	TCIM-2006-IJCIM-0015
Manuscript Type:	Special Issue Paper
Date Submitted by the Author:	01-Feb-2006
Complete List of Authors:	Brecher, C; WZL Aachen University, Chair of Machine Tools Vitr, Mirco; WZL Aachen University, NC-Technology Wolf, Jochen; Muhr und Bender KG, Konstruktion & Entwicklung Nocken/-wellen
Keywords:	INSPECTION, CMM, CNC, INSPECTION PLANNING, STEP NC, STEP
Keywords (user):	ISO 14649-16, closed process chain
Note: The following files were submitted by the author for peer review, but cannot be converted to PDF. You must view these files (e.g. movies) online.	
fig1.emf fig2.emf	

IESM-05 Special Issue

Closed-loop CAPP/CAM/CNC process chain based on STEP and STEP-NC inspection tasks

C. BRECHER†, M. VITR*† and J. WOLF‡

†WZL of Aachen Technical University, Germany
‡Muhr und Bender KG, Germany

Correspondence *M. Vitr. Email: m.vitr@wzl.rwth-aachen.de

The object-oriented STEP-NC programming interface supports a bi-directional data exchange between CAM (Computer-Aided Manufacturing) systems and CNCs (Computerised Numerical Controllers), and by that helps to integrate the CNC into the CAx world. In this context this paper introduces the integration of measuring technology into the STEP-NC based process chain, to be able to preserve the results of the manufacturing process in a set of data and feed them back to the planning process. In particular this paper describes the current draft of ISO 14649 Part 16 - Data for touch probing based inspection - which allows the integration of inspection tasks into a sequence of machining operations. It gives a short overview of how Part 16 fits in with other inspection data exchange standards and draft standards, such as STEP AP219, DMIS (Dimensional Measuring Interface Standard), DML (Dimensional Markup Language) and I++DME. Furthermore, a prototype demonstration scenario for the closed-loop process chain is presented, which includes generation and execution of a STEP-NC program and feedback of measured results, achieved by automatically controlled STEP-NC inspection tasks, to the CAM system.

Keywords: ISO14649-16; Inspection; AP219; DMIS; DML; closed process chain

1 Introduction

The STEP-NC (ISO 14649) data model provides a higher level of information at the CNC including geometric information of a workpiece, and hence enables a bi-directional information exchange with the different software systems involved in the manufacturing process. Since the data model is compatible with ISO 10303 (STEP), as one of the major data models for geometry data exchange between CAD/CAM systems, the standard offers an interface for constant forwarding of product information to CNCs as well as inspection planning systems and coordinate measuring machines (CMMs) without the necessity of conversions or redefining geometry (Pfeifer and Effenkammer 2000, Pfeifer *et al*. 2002, Effenkammer 2002, Glombitza 2004). Thus, only technology information has to be added in order to generate the manufacturing or the inspection program.

In combination with shop floor oriented programming (SFP) tools, which allow the graphical representation and intuitive modification of the STEP-NC data, the higher quality of information of STEP-NC makes it possible to understand existing part programs in order to modify them at the shop floor. Modifications in the part program, such as technology data or process sequence, can be saved and fed back to the planning department, enabling the exchange of experiences between the shop floor and the planning department. Thus, changes will not be lost when a new part program is created or the existing part program is called again the next time. This way the NC program, unlike a conventional ISO 6983 (G and M codes) program, remains not only as a list of instructions to produce one specific part on one specific machine tool, but becomes useful for information exchange between the process planning department and the shop floor.

From the end-users point of view STEP-NC not only eliminates the costly and inefficient process of post processing, but also establishes a collaborative environment for the exchange of information between product design applications, manufacturing process planning, and the machine tool on the shop floor (OMAC 2002). By allowing feedback of changes and process information to the planning level, it enables the realisation of a closed STEP-NC based process chain with data feedback and consistent data on every level (Figure 1).

Up to now the focus in developing the STEP-NC data model was to enhance the link between process planning and manufacturing in the forward direction from process planning to machining of the workpiece. This was done with the goal to simplify the process of NC-programming (by guiding the operator through automated process proposing based on machining features and technology specific operations) or even completely avoid the necessity of user interaction to create the NC program. Up to now, STEP-NC implementations which realise a truly closed process chain with a bi-directional information flow, including feedback of measurement results to process planning, are nonexistant. However, a first prototype of a closed process chain which fully integrates inspection into the STEP-NC information flow was demonstrated by the Laboratory for Machine Tools and Production Engineering (WZL) at Aachen University (Germany) during the final review of the IMS STEP-NC project (IMS 2001) in 2004. The demonstration scenario includes the milling of a workpiece, inspection of several workpiece features and feedback of the measured results into the product model. The prototype is described later in this paper.

The paper investigates the possibilities of data feedback to enhance the link between machining (CNC) and process planning (CAPP/CAM) and hence improve production efficiency. Working sequentially, CAM and CNC cannot accomplish closed-loop machining. For optimum manufacturing results and flexibility, both systems must be seamlessly integrated. To fully close the manufacturing loop, inspection has to be included to be able to feed back measurement results obtained by inspection tasks for process optimisation and documentation purposes. The focus of this paper lies on the closure of the complete process chain by integrating inspection activities into the STEP-NC based process chain and by feeding back the results of the manufacturing operation in terms of the obtained measurement data back to process planning.

2 Closed process chain

The process chain applied in industrial manufacturing and inspection is characterised by a complex sequence of manual and automated activities based on various software applications and exchange formats. A number of irreversible data conversions with loss of accuracy and context, hinder a seamless information flow, and the feedback of measurement information to the preceding levels of planning, NC-programming and machining requires large effort and results in information loss. STEP-NC for the first time offers a uniform data interface for computer-integrated manufacturing with a closed loop from the planning of the machining operation to the machine tool, the inspection of the manufactured result and back to the production planning process (Figure 1). Based on the integrated STEP model, there is context information available and preserved throughout the whole manufacturing and inspection process, which enables linking of the acquired inspection results to the corresponding manufacturing operations.

[Insert Figure 1 about here]

The STEP-NC data model for inspection (ISO 14649 Part 16), which defines inspection tasks based on STEP data and the other STEP-NC Parts, allows to realise a closed process chain by enabling process integrated inspection, i.e. the integration of inspection activities into machining programs, and by facilitating the automated seamless data feedback of the measurement results in a feature-based product model. This possibility is important in terms of process optimisation and documentation. The results of the process-integrated inspection tasks can be used for adjustment of positions (e.g. raw part, zero offset) as well as for data acquisition to decide on optimal work plans or for quality assurance. The results can be used for planning of subsequent manufacturing operations, for example to compensate systematical errors in future manufacturing. Furthermore, based on the integrated STEP data, changes made to the shape of the workpiece for example can automatically be taken into account for the automated generation of a new measuring program.

3 Metrology standards

The information flow of the manufacturing and inspection process chain, which is depicted in Figure 2, typically starts with the design data, which defines the workpiece geometry including the tolerances. This design data is used as input for manufacturing planning of the part as well as for inspection planning and the generation of inspection programs. Whereas the manufacturing process chain is already seamlessly realised based on STEP-NC data, up to now, no STEP based data format exist, which allows conversion-free data exchange between the inspection software systems. In this paper, the focus will be laid on the metrology process chain and the corresponding data formats.

[Insert Figure 2 about here]

3.1 Existing inspection data models

Metrology systems typically include several components for definition and execution of the inspection tasks and analysis of the results (Planning, Execution, Reporting & Analysis software; Figure 2). These components communicate using either proprietary or standardised communication languages and data formats. Apart from the numerous proprietary formats still often used for programming and storing of the results, there are two widely-used standards for the exchange of inspection process information and measurement results respectively. The exchange of inspection process information is standardised in DMIS (ANSI 2001) and the exchange of measurement results is defined in DML (DML 2004). The new STEP standard for dimensional inspection process planning (ISO 10303 AP219) and its relation to ISO 14649 Part 16 are described in the following section.

DMIS provides a mechanism for integrating dimensional inspection planning and execution systems by defining a neutral format for the communication of inspection process information. The DMIS communication protocol was created as standard to allow the preparation of inspection programs and the communication of inspection data between computer systems and inspection equipment regardless of the vendor (Mills 1999).

After the inspection plan, i.e. the measurements to be done, is defined, the information of this inspection plan is interpreted by the inspection execution software which, based on this information, creates an inspection program for the specific measurement operations. The resulting inspection program consists of (often machine or vendor specific) low-level inspection instruction commands that are needed to control the measuring hardware. To be able to run any programming/execution system on any compliant coordinate measuring machine, the I++DME Specification (ia.cmm 2003) was created, which specifies the low-level inspection instruction commands used to drive the measuring hardware. However, since I++DME is only used to drive the CMM, it has to be seen independently of the data formats for inspection planning and storing of the results.

The measurement data, i.e. the results of the inspection operation, typically are transferred to reporting and analysis software, using DML. The standardised data format is needed to avoid conversions, since measurement data feeds into reporting and analysis from various sources. DML specifies the data transfer of dimensional results between inspection devices which pass data to databases to be used by reporting and analysis applications (DML 2004, Schafer 2004). The DML specification defines and documents the data format and content requirements for the exchange of dimensional inspection results between these systems, based on XML technology. The DML specification with its supported features and tolerance types has been harmonised with DMIS as well as AP219, which is introduced in the following.

With DMIS it is possible to integrate inspection planning data and results into manufacturing systems. However, this standard is not strong in providing the integration between inspection results and reporting and the original design with its dimensional tolerances (Vorburger 2000). The standard is not integrated into the STEP world, since it has no direct access to the STEP and STEP-NC data defined in CAD and CAM. Furthermore, inspection results have to be stored in another file and format (DML), which again requires unwanted data conversions and can lead to data inconsistencies. Both formats (DMIS and DML), in contrast to STEP-NC, are not feature based and thus do not allow to preserve the context of the manufacturing features and the workingsteps. To realise a seamless, closed process chain without data conversions and inconsistencies, inspection has to be fully integrated into the manufacturing information flow based on STEP. If the inspection information is based on STEP, it can be used in all subsequent process steps without the need of redefining this information. Based on geometric dimensioning and tolerancing (GD&T) data defined in the CAD system, the STEP data model provides the means for automatic inspection programming as well as automatic post inspection analysis.

3.2 STEP-compliant inspection data models

In order to enable the exchange of inspection information between the various systems that create and use inspection information, based on STEP principles, the STEP AP219 information model - Dimensional Inspection Process Planning for CMMs - for dimensional inspection was created. STEP AP219 is working towards a standard for inspection planning which will be fully integrated into the STEP data flow. It specifies a neutral file format for GD&T data with defined inspection features and including all inspection tolerances.

To be able to perform inspection operations in a STEP-NC manufacturing environment, STEP-NC Part 16 was created. This part of the ISO 14649 standard allows a user to define and integrate inspection workingsteps and the required operations into manufacturing programs and avoids data conversions and duplication of effort, since it can directly use STEP data. This data model addresses the exchange of inspection tasks, their results and the circumstances of these results. In contrast to AP219, which focuses on data exchange, Part 16 focuses on the operational aspects, i.e. the motion planning and the control of the measuring hardware.

STEP-NC Part 16 offers the necessary data structure for the exchange of GD&T data as well as process information. In contrast to DMIS and DML, using STEP-NC Part 16, result data is directly included in the file and does not have to be converted for other Part 16 conform software systems. STEP-NC enables a closed, feature based data exchange in production and the ability to provide tolerance, inspection and result data in a universal way from design to manufacturing and back to design. Based on the feature information, the manufacturing context can be preserved.

The goal of STEP-NC is to directly interpret the process plan inside the controller of the CMM and feedback the result as well as the interpreted result via the data set. A visionary scenario would be the automated generation of machine movements by the CMM based on STEP-NC data. If STEP-NC is directly interpreted by the CMM, CMM programs do not have to be regenerated if parts are moved to different machines. If a certain CMM is not capable of interpreting the STEP-NC data directly, it is still possible to use post-processors equal to CNC post-processors to translate the general data into execution commands for the CMM (i.e. I++DME) and thus make the whole system STEP compliant.

The integration of inspection into the STEP-NC standard allows to directly access existing STEP and STEP-NC data sets, and, if fully integrated, no additional measurement programs have to be created but the CMM is controlled by the same STEP-NC file. One data set instead of single, stand-alone files can be used and feedback as well as relation of results to originating data become possible.

The universal use of STEP-NC data allows to preserve the context of the features and part information. As the tolerances are related to features, the measured results can also be assigned to these features. This is the major difference to the existing standards DMIS and DML. Instead of just knowing that something is out of tolerance, STEP-NC inspection provides the information where it is out of tolerance and what else is affected by the deviation. For example, the workingstep sequence as defined in the workplan, and its effect on the achieved tolerances can be evaluated. Moreover, the operator as well as the designer can talk about the deviation based on the feature or the current workingstep. Thus, it becomes easier to discuss the reasons and the consequences.

STEP AP219 and ISO 14649 Part 16 are still in draft state. They discuss topics of inspection based on the exchange of results (AP219) and, respectively, the integration of inspection into process planning and NC machining (ISO 14649). An ideal solution would be to have a well defined interface allowing AP219 to focus on results and to be used in ISO 14649. For the time being the complexity and amount of geometry elements allowed by AP219 is too powerful for ISO 14649 and will hinder the realisation in CMM controls. Thus a subset is needed. This could be achieved by conformance classes or the same way it was done by ISO 14649 and AP238, using the different ARM/AIM models.

4 ISO14649-16 defining a data model for touch probe based inspection

The data model of ISO 14649 Part 16 (working draft) - Data for touch probing based inspection - is built upon the basic STEP-NC process model (ISO 14649-10) and protocols of ISO 10303. The data model allows the integration of machining and inspection operations in one single STEP-NC program, i.e. the integration of inspection workingsteps into a sequence of machining workingsteps. It also allows storing the inspected results.

Together with the general process data described in ISO 14649-10, Part 16 describes the interface between a computerised numerical controller and the programming system (i.e. CAM system or shop floor programming system) for inspection. Part 16 can be used for inspection operations on all types of machines, be it specific measuring machines or for online inspection during the machining process for example on milling machines or machining centres. It focuses on touch probing operations, which can either be executed with a touch probe on a CNC machine tool or on a CMM. Other inspection methods, like manual inspection activities or optical measuring etc., are out of scope of the standard for the time being.

4.1 Inspection data model defined in Part 16

Subject of the *inspection_schema*, which is described in Part 16 of ISO 14649, is the definition of technology-specific data types representing the inspection process using touch probes. This includes both inspection of freeform surfaces as well as inspection of prismatic workpieces (also known as 2½D).

An inspection task has to contain information on geometry, tolerances and inspection conditions. Part 16 follows the basic STEP-NC approach to separate geometry and technology information, to be able to change technology information independently of the fixed geometry information. According to the other technological parts of STEP-NC (e.g. Part 11 for milling), the Part 16 data model defines so called probing workingsteps which include inspection operations and inspection items.

Figure 3 contains a simplified abstract of the core data elements as defined in ISO 14649 Part 16. It shows how "What to measure", represented by inspection items, and "How to measure", specified in probing operations, are defined separately and then combined in a workingstep. This *probing_workingstep*, which is defined in Part 16 as a subtype of the Part 10 *touch_probing* entity, allows the integration of an inspection operation into the workplan of a STEP-NC manufacturing program.

[Insert Figure 3 about here]

Each probing workingstep references a single inspection item or a set of inspection items, which contain tolerance information, and a *probing_operation*, which has to be executed in order to inspect the given inspection items. The inspection items map the nominal values and tolerances of a workpiece (geometry) and reference one or several manufacturing features on which the inspection operation (technology) is performed. The probing operation contains the probing strategy and circumstances (probing tool, reference datum). Depending on the defined strategy the movements of the CMM for the certain workpiece are calculated. A STEP-NC capable CMM might be able to calculate the optimal movements automatically based on the given strategy. However, due to the high complexity and the large number of possible strategies (approach moves, speed, etc.) these cannot be included in the standard, and instead have to be defined by the user for each specific application.

To be able to define any strategy using the data model, the *probing_strategy*, which is the only probing operation for the time being, allows the definition of arbitrary CMM or CNC vendor-specific probing tasks by usage of unique strings which identify a specific strategy. These proprietary strings are predefined by each vendor.

Of course it would be thinkable to add some simple "standard" strategies, however, the number of possible tolerances, relations and geometries in conjunction with different strategies and evaluation models would result in a too complex data model. The various combinations, exceptions etc. would hinder the acceptance and implementation of Part 16 by the system providers. So until CMM vendors will manage to find a common set of commands and common operations and strategies, it is necessary to have the possibility of vendor specific strings.

There are several initiatives looking for a standard to define 'How to measure". This standard is required for planning as well as for data evaluation. DEMIS, AP219 etc. are mainly focussing on the exchange of measured and evaluated results. They provide no standard for 'How to measure'. The automotive workgroup I++ has tried to define common operations, but could not yet agree on a common subset.

The STEP-NC standard itself focuses on the measuring activities as workingsteps, to be able to separate and group them. The definition of inspection operations and inspection strategies is out of scope of the standard, as the data model of Part 16 aims at an exchange protocol and is not designed to provide solutions for current implementation problems and proprietary in-house knowledge. In general, it is important to realise that STEP-NC only defines a basic data model but does not contain any intelligent functionality, which is often misunderstood. Any intelligent functionality has to be implemented separately in the control systems of the machines.

A *reference datum* is needed to relate the measured values or positions to, and can be defined by simple geometrical elements (describing a coordinate system) or features. Each probing operation is limited to the use of one touch probe, which is used to run the tactile measuring operation on a CMM or a CNC machine tool. The different types of probes are described by the abstract *touch_probe* entity. However, since there is no STEP-NC tool standard for touch probing tools yet, the definitions in the data model of Part 16 are held general up to now. If there will be a STEP-NC tool standard for inspection and how this standard will look like, will depend on the ongoing STEP-NC standardisation work.

The *inspection_item* entity provides a container to attach tolerances to geometrical elements. It contains the toleranced item and provides the necessary container to pre-process and store the result. The toleranced elements can be attributes of features (e.g. diameter of a round hole), relations within one feature (e.g. distance between two sides of a pocket) or relations between two different items (e.g. distance of the centre-line of two holes, perpendicularity of a hole towards a plane) (ISO14649-16 2004). The result is stored together with the circumstances by which this result was generated. Furthermore, the workpiece inspection model to be applied to evaluate the probed data is referenced.

The measurement results obtained by the inspection operation are assigned to the corresponding features to maintain the relation between tolerance and feature. The function of storing results, proposed by this data model, does not modify existing geometry elements within a ISO 14649 data set. Results are stored in additional elements. Geometry provided by CAD or CAM will not be modified, but only be used as input to an inspection task. The main benefit of this approach is that data structures, which do not offer tolerances and containers for results, can be used within this data model (ISO14649-16 2004).

The task to correlate the results with the tolerances and dimensions defined by CAD and CAM has to be solved by the different applications, based on the provided data structure. The end-users in the STEP-NC project clearly stated that the link between measuring result and workplan / workpiece geometry, as well as the interpretation of the data, has to be generated by the software and should not be stored in the data file. This is due to the fact, that the data set is a snap-shot, which should not include temporary or application-specific data. This means that when a control is waiting for measuring data, it has to provide the corresponding data structure. STEP-NC cannot cover all levels of communication between CNC, CMM, user etc. Ideally the STEP-NC file only contains the minimal necessary data. The rest (access, exchange, analysis, update) has to be handled by the software.

4.2 Feature definitions

A basic difficulty in defining the data model for inspection is that it has to bridge features and shapes. The problem is that features themselves cannot be measured but only single characteristics or attributes of a feature can be measured. This results in the problem, that inspection items cannot be represented independently of the feature, the workpiece including its function or the manufacturing operations. While milling and turning are usually defined by toolpaths or removal volumes, an inspection task is far more complex. One machining feature can contain indefinite variations of items to be inspected. In addition these items can be related to other features. For example, there are many different ways how to measure the different attributes of a pocket with a complex contour. A similar problem applies to the inspection of a simple drill hole diameter. There is not one single diameter for the hole, i.e. the diameter can be different at different depths of the hole. Thus, for the operation, the location at which the diameter shall be measured has to be defined, which requires an additional element in the data model to be able to specify this measuring depth.

The definition of tolerances of the attribute and the measurement always require geometric elements to relate the tolerance to. The parametric definition of the manufacturing features does not include explicit geometric elements, which are thus missing to allow the inspection of the attribute. Moreover, the semantics of features can be different. The designer for example may have another interpretation of a feature than the machine operator has. Whereas the designer primarily focuses on functional and optical design aspects, the machine operator is interested in manufacturing aspects to create the shape of the feature, i.e. he is interested in the explicit shapes and curves, which are not necessarily directly given by the parametric features of the design model.

The different systems involved in the manufacturing process of a workpiece normally have different demands on the information of a feature. A design system typically needs other data than a planning system for creating a measuring program. Whereas, for example, in CAD a simple rectangular pocket may have been designed by removing a cuboid volume from a block and is represented by its boundary representation, in NC machining, the outer contour, the direction and the depth of the pocket are needed. Inspection again, may require two opposing faces of the pocket to determine the length attribute of the feature.

The data model has to include both, feature information and information for inspection. Thus, additional elements have to be included in a feature-based file. In the data model, these elements add tolerances to features by referencing features of the workpiece. According to the attributes to be measured, the manufacturing features are broken down into elementary inspection features, like for example a cylinder or a plane. With the additional information provided in the file, user and application-specific views then have to filter the data according to the specific demands on the data and its representation.

Part 16 approaches the above problem by defining containers for linking explicit geometry to features. That means each *inspection_item* links an explicit, toleranced item (e.g. toleranced length measure) to a specific parameterised or semantic attribute of a feature. This solution is as well integrated into the model of STEP AP219.

The so-far standardised STEP-NC manufacturing features include selected dimension tolerances, which are easily attained and interpreted by software applications. For these kind of tolerances, the definition of inspection procedures and adequate measured elements requires small effort and is highly consistent between software applications. In contrast to other relevant product models, STEP-NC integrates machine interpretable representations of requirements on machining operations in form of tolerances, executable representations of machining operations as well as executable representations for verification of suitability of machining processes on CMM.

Pose and shape tolerances in the current draft are defined in accordance with German standards (DIN ISO 1101). Since these definitions do not exactly correspond to the harmonised tolerance model of the ISO 10303 application protocols, there is currently work in progress to harmonise the tolerances defined in Part 16 with the harmonised STEP GD&T model. The tolerance model for dimensioning and geometric tolerances developed by ISO TC184/SC4, which has been harmonised across all of the SC4 ISO10303 application protocols (AP224, AP214, AP219, AP238, AP223, AP 240, AP203 2^{nd}ed. and Part 1050 teams), is based on ISO 1101 as well. However, some of the defined entities, describing the same tolerance, have different names and attributes in the two tolerance models. ISO TC184 sub committees SC1 and SC4 currently work together to harmonise the models, so that ISO10303 (AP219) and ISO14649 (Part 16) documents will function together and it will be possible to generate a Part 16 inspection plan from an AP219 file without any conversions. The Part 16 tolerance definitions will be changed to harmonise the two models. Since there have already been harmonisation activities between DMIS, DML and AP219, the final data model of Part 16 is expected to be in conformance with the definitions of these models as well.

5 Prototype implementation of a closed-loop process chain including inspection

The following prototype, realising a closed-loop process chain with bidirectional information flow and measurement information feedback of inspection operations into the STEP-NC file and process planning, has already been demonstrated by WZL Aachen at the final review of the IMS STEP-NC project (IMS 2001). The example scenario was based on an example workpiece, machined on two STEP-NC based contollers (1.) Sinumerik 840D + STEP-NC enabled ShopMill controlling a Chiron machine tool (2.) WZL-NC controlling a Maho 600E machine tool. The milling operation was defined by a STEP-NC milling program (ISO 14649 file) which also included inspection workingsteps. The data flow is depicted in Figure 4. Apart from the dashed lines, the data flow is completely based on STEP-NC data.

[Insert Figure 4 about here]

For demonstration, the STEP-NC program was visualised and edited using the WZL 3D graphics shop floor programming system WZL-SFP. The WZL-SFP provides data masks for manual tolerance and inspection workingstep definition. The same STEP-NC file, containing both, the workplan and working steps for machining and inspection, was then used to measure the machined workpiece on a CMM. To realise the sample scenario, an existing inspection system (Zeiss CMM with Calypso Software) was used. Since up to now no CMMs capable of interpreting STEP-NC feature information are available, the STEP-NC data had to be converted into a suitable format for the prototype scenario. In the scenario, the conversion is done by a plugin of the WZL-SFP software, which converts the STEP-NC feature information into AP203 B-Rep geometry data and Q-DAS (Q-DAS Inc. 2002) inspection data. Geometry information inside the STEP-NC file is re-organised in explicit form and exported into a STEP AP203 file, while inspection criteria are sorted and exported to the Q-DAS format. This inspection information is fed to the CMM using the WEPROM (WEPROM 2005) interface of Calypso. The WEPROM interface was developed with the support of german ministry of education and research (BMBF). With this interface, a direct transfer of product information (geometry + tolerance) from CAD to CMM has been realised, which enables an automatical inspection plan based on CAD data. The basis of the WEPROM interface is the combination of STEP AP203 and Q-DAS. Based on the two imported files the Calypso Software builts an automatical inspection plan. With the complement of measurement strategies, measurement code is generated and sent to the Zeiss CMM.

After the measurements, the feedback of the measured data is also covered by WEPROM and an additional software application (Inspection Converter; Figure 4), to grant the references between the features and the measured points. The Zeiss CMM stores the results in a WEPROM based text file which is then parsed, assigned to the STEP-NC inspection items by unambiguous identifier strings and then reintegrated into the STEP-NC file. Thus, the feature information of the STEP-NC file can be preserved and therefore allows feedback of the measured results into the STEP-NC data format and relating the results to the according feature and workingstep. The mapping is completely hidden to the operator inside the STEP-NC enabled SFP system. The operator simply needs to open the STEP-NC file corresponding to the executed measurement task and then he calls the import routine of the software. The results are then read-in, stored in the STEP-NC data set and visualised to the operator in dialogs with graphical elements indicating the result. As soon as there will be CMMs capable of directly reading STEP-NC data, the conversion step can be omitted.

In the example scenario, three STEP-NC based inspection tasks were performed. These were the measurement of the diameter of a round hole, the measurement of the roundness of the hole (scanning with touch probe) and the position of the hole relative to another one (test part depicted in Figures 1, 3 and 4):

1. Manufacturing of the four small holes (diameter 10 mm) surrounding the large hole (diameter 40 mm) and the large hole with two different workplans (first the large inner hole and then four smaller outer holes or

the other way round), measuring the results regarding circularity and position tolerances and evaluating process plan ability.

2. Manufacturing of the large hole in two different ways (drilling and mill cutting), measuring of the two results and evaluating the technology ability with regard to cirularity and position tolerances.
3. Manufacturing of two 10 mm holes, measuring the position tolerance referenced to each other and evaluating the machine tool accuracy.

The results were fed back into the STEP-NC file and visualised in the WZL-SFP software. Visualisation can be done graphically (e.g. in the case of circularity by drawing the required and the measured circle) or textually by displaying the deviation value(s). From this evaluation a conclusion regarding change of technological parameters and reworking the workpiece can be drawn. Based on the measured results, the design, the tolerances of the feature, the technology, the applicability to different machine tools and the workplan's sequence were rated.

The feed back of the measured results is one of the major benefits. Unlike conventional systems, all data can be preserved and fed back based on the context of geometry (e.g. features) and the applied processes (e.g. workplan). Via the workingstep, a tolerance is no longer just limited to geometric elements, but also to a workingstep sequence and an operation. Thus the measured result can be used to rate the workpiece and its geometry as well as the selected manufacturing process.

Even as the complete process chain is not yet available (STEP-NC enabled CMM), the complete closed data flow from process planning over manufacturing and inspection back to process planning was realised and the functionality and the benefits of the STEP-NC integrated inspection have been demonstrated. The executed tests proved that the integration of inspection workingsteps into the machining workplan allows to investigate the effect of the process plan and to take decisions on how to optimise manufacturing. Isolated, geometry item related tolerances and measured results cannot provide this benefit, as the context information (workplan, feature) is missing.

6 Conclusions

The advantages of a standardised data format are obvious. Inspection tasks can be performed on several inspection systems and the resulting measurement data can be consolidated, which allows a unified data management and company-wide evaluation of results. Due to the standardised output, any standard-conform analysis software can evaluate the results. No data conversions, which could cause data loss and corruption, are necessary. By using a standard, any products that support the standard can easily interconnect and flexibility in choice of components is gained, allowing users to choose the best or the least expensive product without any commitments to proprietary products (AIAG-MIPT 2004). Training and maintenance costs can be reduced since the same inspection planning and programming systems can be used for different CMMs. Moreover, based on a standard, programs can be run on all compatible execution systems without the need of program translations or reprogramming.

STEP-NC Part 16 - Data for touch probing based inspection - promises a higher level of automation for the creation of measurement programs and analysis of measurement results and allows to reduce time and unnecessary costs. With Part 16, STEP geometry, such as machining features, can be reused to define inspection tasks. To be able to tolerance parameterised manufacturing features, the data model adds elementary inspection information to these manufacturing features. Measurement results can be related to manufacturing features and manufacturing operations and thus allow the analysis of influences of the chosen manufacturing sequence and strategy. Based on the feature-related evaluation in combination with the work plan, tolerances and results can be related to specific workingsteps and thus optimisation possibilities can be derived. Furthermore, this allows the discussion of results based on common features instead of abstract result tables. Thus, process and product optimisation can be performed easier and more efficient.

There is still work to be done for the tolerance definitions of Part 16. To increase acceptance by allowing simple data exchange and overcoming the problem of data conversions, it is important to harmonise the tolerance models of all existing standards for the overlapping parts of the models. In addition the CMM vendors should be invited to define common operations and strategies for inspection. It is a crucial necessity to have comparable definitions in order to be able to interpret and exchange measured results. Otherwise the undefined circumstances, by which the result was generated, will hinder the described vision of a universal data exchange and reuse.

General feasibility of the data model has scientifically been proved by WZL at Aachen University, where the complete closed process chain including the feedback of measurement data has been shown. The described scenario did prove that the developed data model for inspection provides the required data to run a CMM and is able to feedback the measured results. However, up to now the data model is only a draft and there is still work to be done to improve the data model and make it ready for use. Furthermore, practical implementation has to prove applicability of the data model and industrial feasibility for a closed process chain. The next step will be to promote STEP-NC industrially by demonstrating the benefits of the new concept to the wide public to enhance its acceptance and push forward the further development. This requires extensive collaboration and cooperation with industrial partners who can cover the complete process chain from design over process planning and manufacturing down to inspection. Finally, it must not be forgotten, that STEP-NC itself is a passive data model and does not include any intelligent functionality. These intelligent functions have to be implemented independently of the data model. There is a need to implement new applications that utilise the STEP-NC data model and demonstrate the advantages of the standard. These implementations will show, if the STEP-NC data model is feasible for industrial manufacturing processes, and whether its advantages can be fully exploited or not.

References

[1] ANSI/CAM-I 104.0-2001, Part 1, 2001, DMIS 4.0 Standard, Part 1, Available online at: http://www.cam-i.org/storelistitem.cfm?itemnumber=8 (accessed 20 01 2005)

[2] AIAG-MIPT (Automotive Industry Action Group - Metrology Interoperability Project Team), Interface Standards for Metrology, NIST Presentation from IMTS 2004, 2004

[3] Brouer, N., *NC-Steuerungskern mit Datenschnittstelle für eine Autonome Produktionszelle*, 2000 (Shaker: Aachen).

[4] DML specification committee, 2004, DML - Dimensional Markup Language Version 2.0, Available online at: http://www.dmlspec.org (accessed 20 01 2005)

[5] Effenkammer, D., *Entwicklung einer durchgängigen und CAD-basierten Prozesskette für die Qualitätsprüfung mit Koordinatenmesstechnik*, 2002 (Shaker: Aachen).

[6] Glombitza, M., *Steigerung der Autonomie fertigungsintegrierter Koordinatenmesssysteme durch flexible Bearbeitung*, 2004 (Shaker: Aachen).

[7] IMS Project 97006 (STEP-NC), 2001, STEP-NC - STEP-Compliant Data Interface for Numeric Controls, Available online at: http://www.ims.org/projects/project_info/step_nc.html (accessed 20 01 2005)

[8] IMS STEP-NC consortium, Description of the prototype CAD-CAM-CNC chain for inspection, Project Deliverable ID6.5.2, 2004

[9] International Association of Coordinate Measuring Machine Manufacturers (ia.cmm), 2003, I++DME 1.40 specification, Available online at: http://www.iacmm.org/wgroups/standard.htm (accessed 20 01 2005)

[10] International Organisation of Standardisation, 1983, DIN ISO 1101, Technical drawings, geometrical tolerancing; tolerances of form, orientation, location and runout; generalities, definitions, symbols on drawings

[11] International Standards Organisation, 2004, ISO/WD14649-16, Data model for Computerized Numerical Controllers – Part 16: Data for touch probing based inspection

[12] International Standards Organisation, 2004, ISO/WD10303-219, Industrial automation systems and integration - Product data representation and exchange - Part 219: Application protocol: Dimensional inspection information exchange

[13] Kramer, T. R., 2001, Analysis of Standards Needs for Automated Metrology, Presentation, Knowledge Systems Group NIST, Available online at: http://www.isd.mel.nist.gov/projects/metrology_interoperability/presentations/AnalysisKramer0501.pps (accessed 20 01 2005)

[14] Li, R., *Agentenbasierte NC-Planung für die Komplettbearbeitung auf Dreh-/Fräszentren*, 2001 (Jost-Jetter: Heimsheim).

[15] Mills, K. 1999, Demystifying DMIS, Quality Digest, Available online at: http://www.qualitydigest.com/oct99/html/dmis.html (accessed 20 01 2005)

[16] NIST, Manufacturing Engineering Laboratory, Intelligent Systems Division, 2004, Metrology Interoperability: Interface Standards for Components of Dimensional Metrology Systems, Presentation, Available online at: http://www.isd.mel.nist.gov/projects/metrology_interoperability/

[17] Official ISO/TC184/SC4 Web Site, Available online at: http://www.tc184-sc4.org/ (accessed 20 01 2005)

[18] Official STEP-NC page, Available online at: http://www.step-nc.org (accessed 20 01 2005)

[19] OMAC STEP-NC Users Group, 2002, The Value Proposition for STEP-NC, Technical Report, Available online at: http://www.omac.org/wgs/MachTool/STEP-NC/Deliverables/STEP-NCValuePropDraftV.4.pdf (accessed 20 01 2005)

[20] Pfeifer, T. and Effenkammer, D., Demands on manufacturing metrology and solutions, Technical Report, WZL, Aachen University, 2000

[21] Pfeifer, T., Bruscas Bellido, G. M. and Glombitza, M., An Integrated Inspection Planning System for Autonomous Production, Technical Report, WZL, Aachen University, 2002

[22] Q-DAS Incorporated, 2002, Q-DAS, Q-DAS ASCII Transfer Format, Format Specification, Available online at: http://www.q-das.com/homepage_e/download/dataformat_me_e.zip (accessed 20 01 2005)

[23] Schafer, J., Dimensional Markup Language, DML General Presentation, 2004

[24] Vorburger, T., 2000, Dimensional Inspection Information Exchange, SIMA project description, Available online at: http://www.mel.nist.gov/div826/msid/sima/01_dimensional_insp.htm (accessed 20 01 2005)

[25] Weck, M. and Wolf, J., The Machine Tool's next step: STEP-NC, AMST'02 Advanced Manufacturing Systems and Technology. Proceedings of the Sixth International Conference, Udine (Italy), June 20-21, 2002 (Springer: Wien New York).

[26] Weck, M. and Wolf, J., ISO 14649 Provides Information for Sophisticated and Flexible Numerically Controlled Production, *Production Engineering – Research and Development, Annals of the German Academic Society for Production*, 2, 2003

[27] WEPROM – Werkergerechte und Prozesskettenoptimierte Messtechnik für die Produktion im 21. Jahrhundert, Project Homepage, Available online at: http://www.weprom.de (accessed 20 01 2005)

Figure List