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ADVANCED OPEN CNC SYSTEM WITH IN PROCESS TOOL PATH COMPENSATION

Despite several technical advances over the last decade, CNC controlled manufacturing still bases upon outdated paradigms: manufacturing data are generated and transferred along a heterogeneous and divided CAD/CAM/CNC data chain. The role of the NC controller is limited to the execution of tool paths generated beforehand and the possibility of online tool path adaptation is not planned in legacy NC controllers. In contrast, practical observations make this legacy approach quite inappropriate in an industrial framework. Significant geometrical variability is sometimes observed both prior and after milling in parts that belong to the same batch. In that context, the integration of online tool path adaptation strategies appears to be essential. In this paper, a methodology for correcting the tool path in real-time thanks to measurements provided by a laser scanner moving with the tool is introduced. The resulting local information is used to approximate the workpiece exact geometry by using a POD (Prosper Orthogonal Decomposition) snapshot technique and to adjust the path in accordance. This method has the great advantage of taking into consideration geometrical features such as curvature, twist but also additional parameters whose impact on the tool path is significant (unexpected initial setup of the part for example). This method has been implemented on the advanced CNC programming platform of the laboratory, which hosts in particular a high speed machining centre equipped with an open NC controller.

1. INTRODUCTION

The manufacturing area has benefited from various progresses over the last decades: the equipment has become faster, smarter and safer to face today’s global challenges. However, CNC programming is somehow still based on dated practices and habits. This mostly comes from the use of ISO 6983 data standard, as known as G-codes [1]. The manufacturing data chain is consequently composed of disconnected elements that are using vendor specific formats to exchange CAD/CAM/ CNC information and that are difficult to make communicate together [2].

Hence, manufacturing tool paths are often calculated based on the Computer Aided Design (CAD) model of the part. This numerical model is not always an accurate representation of the physical part and therefore the accuracy of the generated trajectory can be questioned [3]. Once it has been defined and communicated to the Computer Numerical

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Control (CNC) machine tool through a post processor, the number of possibilities for interacting with the machine and modifying in real-time this preconceived tool path are quite reduced, [4]. In the industry, where high production rates are needed, the same tool path is generally used to perform a given milling operation on parts of a same batch, whose geometry is expected to be similar. However, practical observations demonstrate that this conventional approach is unsuitable for guaranteeing a proper accuracy in some situations. On the one hand, forging operations or heat treatments [5], induce internal stresses in the part and finally lead to a distortion during cutting operations made prior to milling.

This paper introduces a methodology for correcting the tool path in real-time thanks to measurements provided by a laser scanner moving with the tool. Section 2 of the papers introduces the state of the art. Section 3 focuses on the proposed method, which is validated through an experimental study. Finally, section 4 discusses the implementation of this method on the high speed machining centre of the laboratory equipped with an open NC controller.

2. STATE OF THE ART

Tool path generation is the subject of extensive research works whose first objective is to fill in some lacks inherent to the use of G-code programming (ISO 6983) on CNC machines tools. Indeed, an accurate tool path definition often requires more data than the simple sequence of tool positions with a theoretical feedrate between each point available in the G-code and most authors have understood the necessity to counterbalance the lacks of legacy CNC approaches. The works can be classified into two categories: experiment-based methods, using cutting force statements and simulation methods, using results of computer simulation.

In [6] Zuperl & al. based their approach on a fuzzy control strategy. Cutting force data are acquired thanks to a Kistler dynamometer and treated with an external force control software suite that adapts the feedrate. Some other methods are based on monitoring strategies, such as [7]. The main limitation of these methods is that a first part needs to be manufactured to initiate the optimization algorithms, which results will be used for the following workpieces. Moreover they do not propose any cutting condition modification during the milling sequence. Many methods employ 3D component dynamometers to acquire cutting force data. In practice, a specific interface must be added to the classical fixture on the table of the machine; measurements provided by the dynamometer are reliable in a restricted volume that should contain the workpiece, whose dimensions are therefore limited. The presence of dust and lubricant may alter the performances of the apparatus. Vibrations induced during cutting may also degrade measurement quality. For these reasons, these devices cannot be efficiently exploited in the industry.

Other authors employed simulation results to optimize cutting parameters. For instance, Li & al. propose in [8] a method based on cutting force prediction. Tool paths are divided in segments. Feedrate can be modified on each new segment; the values are obtained thanks heuristics algorithms. At the end of the optimization, feedrate variations are programmed for the whole part and the program can be put into the CNC controller.

Simulation results can be employed to further improve the process by acting on the tool path. Hence, from the tool deflection results, tool path compensation algorithms have been developed to decrease milled surface errors in [9]. The main purpose of such application is to obtain a compensated tool path that can minimize the errors caused by tool deflection. Tool deflection is calculated within the dynamic analysis module of the HSM simulator, by using a cantilever beam model. To speed up the computation times, the deflection position of the tool centre point is considered rather than the whole shape of the tool. Fig. 1 presents the interest of such method by comparing two cases, one with and one without tool compensation.

The proposed tool deflection compensation method consequently assesses the interest of taking advantage of simulation results to improve the machining process. By modifying the theoretical the tool path so that the real tool position due to deflection is located at the desired (nominal) position, milled surfaces properties are enhanced.

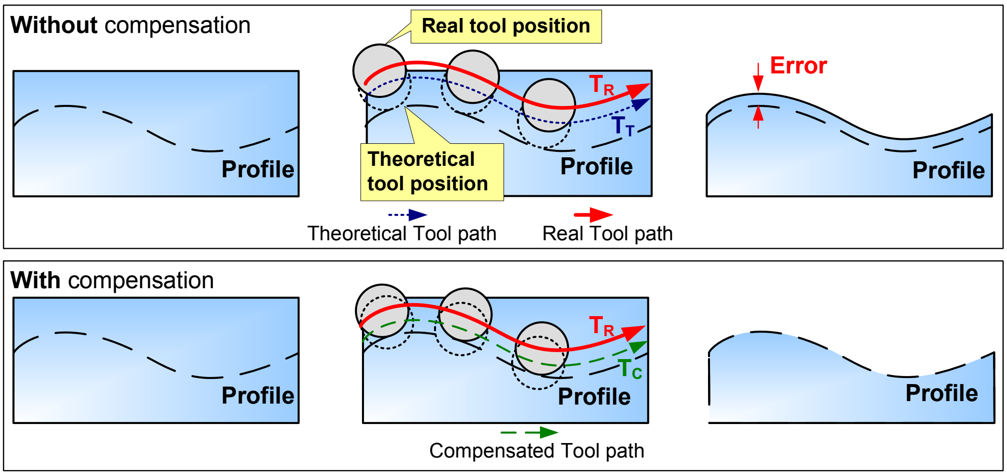

Fig. 1. Compensated tool path from tool deflection computation [9]

Intelligent Computer Aided Manufacturing (ICAM) first introduced by Hascoet et al. is based on this observation [10]. It suggests the use of Direct Numerical Control (DNC) process data in order to get rid of additional devices. Cutting forces are not directly measured, but computed from the torques in the actuators of the machine. Nevertheless, a dummy run must be completed in order to determine kinematic torques necessary to move the tool.

3. ONLINE TOOL PATH COMPENSATION

The method discussed in this paper fits directly the ICAM approach, as it is a combination of real time process data that feed a simulation algorithm running in parallel to machining. Tool paths are compensated on-line according to the algorithm outputs.

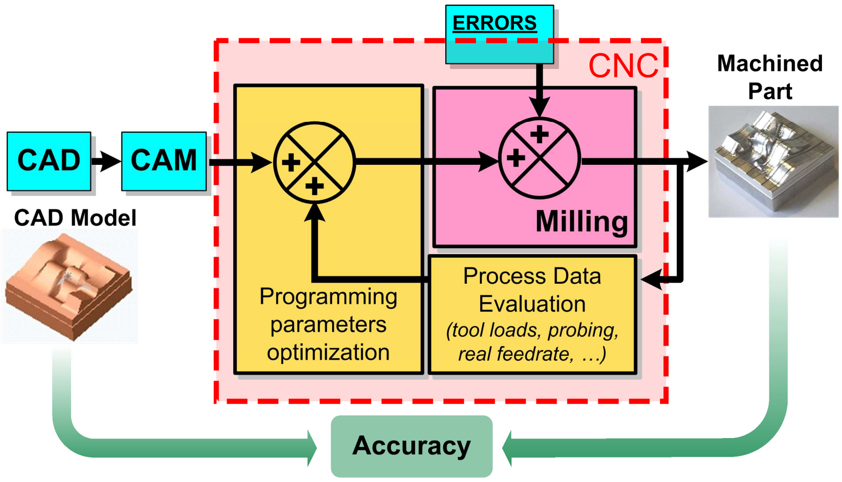

Fig. 2. The ICAM approach [10]

A closed-loop machining scheme involving measurement and data-processing steps is set up, as shown in Fig. 2.

Online process data acquisition includes two distinct phases, the learning phase and the tool path update. During the learning phase, online measurement is undertaken but the path is not modified. The nominal tool path is used and therefore the machining operation may not be accurately performed. Consequently, both the duration of the learning phase and the shape of the path traveled by the tool during this phase must be adapted to the actual process implemented on the machine tool. This phase comes to an end when the amount of measured data is sufficient to derive an accurate update for the tool path.

Then, during the tool path update phase, the altitude of the tool positions are modified compared to the nominal path in order to fit to the actual workpiece geometry. Online data acquisition is still carried out until the manufacturing operation stops. Measurements performed during this phase also serve for monitoring and verification purposes: malfunctions are detected and decisions are taken accordingly.

3.1. REAL SURFACE COMPUTATION BASED THE POD METHOD

The Proper Orthogonal Decomposition (POD) is an efficient technique to extract relevant information from a large set of data. From a mathematical point of view, the dimension considered here being finite and the decomposition being truncated, the POD is equivalent to the Principal Component Analysis (PCA) [11].

In this paper, this technique is implemented for surface approximation. From a large set of surfaces called "snapshots", a reduced basis of modes or "principal surfaces" is extracted and used as a basis of approximation for the actual geometry measured online.

There are typically two ways of obtaining an initial family of snapshots for the surface to machine. The first one is to use data coming from previously measured parts. These data are set up as a priority since they come from practical observation and do not require any mathematical simplification or model. Nevertheless, the inspected parts must be similar to the parts that are concerned by the study, which limits its availability for practical cases. Another approach for building up an initial set of snapshots is to generate them numerically. Geometrical features such as the type of curvature (single or double), the radius of curvature (only a range is necessary) or for example, the amount of twist, are one of the ingredients used for generating surfaces, thanks to a suited mathematical formulation. The real part can consequently be modeled as a linear combination of known geometrical features, as depicted in Fig. 3.

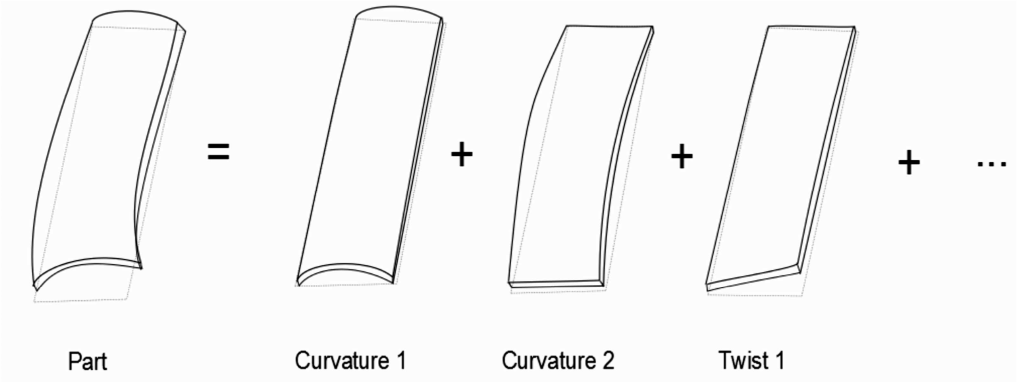

Fig. 3. Real part modelling as a combination of known features [3]

Once the family of snapshots (several hundred) is constructed, an algorithm involving a Singular Value Decomposition (SVD) allows the extraction of a small set of principal surfaces (approximately ten) which will be used to model the part.

As the machining operation goes on, the number of measurements N increases and the minimization problem is solved for the first time when N becomes greater than r, the dimension of the reduced basis. The computational effort is relatively small since only r coefficients must be identified, which makes this approach a good candidate for real-time applications. Moreover, the resulting set of principal surfaces is optimal: all surfaces are orthogonal to each other (with respect to L2 inner product) while minimizing the distance between the original collection of snapshots and its reduced representation. More details regarding those aspects are given in [12].

Another advantage of using a POD basis is that it filters the measurement noise, as long as it stays to reasonable values. Last of all, one limit of this approach is its dependency on the pertinence of the set of snapshots selected beforehand. All information, the features which are required for the approximation of the geometry of the part, must be initially contained in the snapshots. Otherwise there is no way of capturing them in the reduced set of modes.

Various numerical tests have carried out to validate the surface estimation method proposed here. For use cases where the nominal part is a plan and the real one a simple curvature curve, the real part can be approximated with a precision of 0.01mm very as soon as measured data in the two Cartesian directions of the initial plan become available.

3.2. REAL TIME TOOL PATHS COMPENSATION

The second stage of the method is to compensate the tool paths according to the simulation results. This part highly depends on the capability of the CNC controller of the employed machine tool. Hence, for most NC programmed tool paths, the program file contains a list of interpolation points that have sequentially. In an ideal world it would be enough to update the tool paths points coordinates as often as necessary according to the surface approximated by simulation. However, the core design of CNC controller makes any tool path modification hardly possible during the manufacturing process. For safety and repeatability reasons, a running tool path has not to be modified.

When using legacy G-code based CNC controllers, it is consequently necessary to use some tricks of the trade to modify the tool path online. Hence, the use of internal variables to define the control point coordinates is a way out. For example, the control point altitude value is linked to a parameter that is updated by the simulation algorithm according to the surface interpolation results. Unfortunately, this only applies to short tool paths (i.e. with a limited number of control points), as each control points needs at least one machine parameter. This trick is consequently not usable for complex industrial parts.

Simultaneous actions are another way to update the tool path online. It is for example possible to modify some machine parameter values during the machining process, such as cutting tool compensation jogs. This trick is much better than the previous one, but still does not meet all expectations: limited list of available parameters, limited value ranges.

As a result, with legacy NC controllers, the tool path compensation approach needs to be finely tuned according to the selected equipment, which limits the efficiency of the whole approach in terms of genericity and portability. A direct access to the tool path interpolation kernel would solve this issue, but commercial NC controllers are black boxes.

3.3. VALIDATION STUDY

A validation study has been conducted on the VERNE five axes parallel kinematics machine of the laboratory. The NC controller is a Siemens 840D. The objective is to prove the effectiveness of the method by compensating the tool path online according to real time measures. A curved sheet metal is set up on the fixture of the tilting table, on which a constant depth slot is to be machined. The initial tool path is a flat line, the test aims to modify this tool path online to adapt to the real curvature.

A laser scanner is fixed on the machine tool spindle. Its role is to scan the upcoming regions of the sheet metal and provide height information while the tool path is being travelled. This information is then computed by the surface identification algorithm and the tool path compensation algorithm feeds the new tool path control points back to the CNC machine.

Prior to machining, an approach trajectory is carried out to learn the actual geometry and feed the POD basis. Once the tool reaches the part and the cutting operation actually begins, the tool is expected to already be at a correct location. The main challenge in this experiment is not only to derive a correction for the tool path. The transfer of information with the CNC machine tool together with the modification of tool path geometry once the machining program has started is a crucial step.

The results are depicted in Fig. 4, which compares the ideal actual tool path carried out (compensated tool path) with the expected tool path to machine a slot at constant depth on the test sheet metal. The difference of altitude with respect to the ideal path designed from the exact measured geometry does not exceed 0.15mm

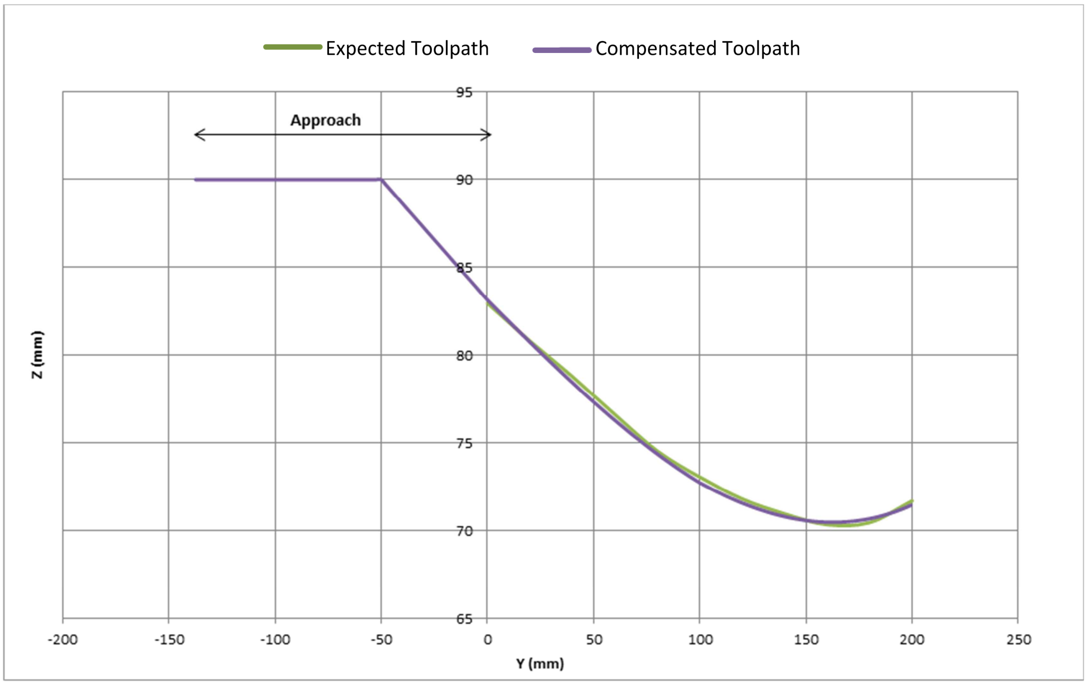

Fig. 4. Comparison of expected and compensated tool paths for a curved sheet metal [3]

The remaining error is mainly due to a lack in the dialogue between the components of the closed-loop machining. In particular, the conformity of the updated path can be improved by enhancing synchronization aspects which are essential throughout this procedure. This experimental study demonstrates the feasibility of an online measurement-based strategy for the update of the tool path. Other tests have been carried out in a conclusive way. For more complex geometries, the POD basis has to be richer and the amount of measurements to collect is increased.

4. OPEN CNC MANUFACTURING SYSTEM

The implementation of the proposed method has to be improved to be more efficient and adaptive to any machining tool path and any CNC controller. As soon as a commercial NC controller is used, there are limitations as this hardware act as black boxes without any access to the interpolation kernel. In contrast, over the last decade, open-NC controller systems have been proposed, such as the LinuxCNC project (formerly known as Enhanced Machine Controller EMC [13]).

To experiment the potential of open NC controller, an industrial functional machine tool of the laboratory, a Cincinnati Milacron 'Sabre', has been updated to operate with the LinuxCNC open controller [14]. It is the first industrial machine of this scale to implement this openNC controller as far as is known. At the same time, the CNC has been extended with the integration of SPAIM (*STEP-NC Platform for Advanced and Intelligent Manufacturing*) so that the advantages of STEP-NC can be exploited.

This implementation with LinuxCNC consists of two on-board computers. On PC1 with Linux OS, the LinuxCNC software and hardware (motion boards, encoders and I/O boards) are installed. The connections between the PC and the machine axes are handled by this station. It is responsible for the real-time motion control based on a RT-Linux kernel. The PC2 with Windows OS contains accompanying software such as CAD, CAM. It is also where the SPAIM platform inhabits and will be responsible for all advanced STEP-NC programming and control.

During these modifications, the Sabre machine was further extended to become an all-encompassing Integrated Test Platform (ITP). The primary goal was to safeguard the functionalities of the original NUM controller, while enabling different guest controllers such as LinuxCNC, Fidia (CNPC 143) and eventually any other NC controller from any manufacturer, to all cohabit within the same machine tool. This allows showing the influence of each controller on the milling process and also to demonstrate each technological potential (smoothing curves, NURBS, optimizations, etc.). It is important to include and use brand name controllers (like FIDIA, SIEMENS, etc.) because they are prevalent in today's industry. To accomplish the general objectives and long term goals, implementations and innovation needs to be usable in the short term by the manufacturing industry.

On the ITP, a hard-wired switch permits switching from one CNC controller to the next and each has complete control on the Sabre machine. The switch represents a physical diversion of the signal sources for the input signals that are used to control the axes (spindle, linear machine axes and hand-wheel). It also changes the signal sinks of the output signals that are sent out by encoders and limit switches.

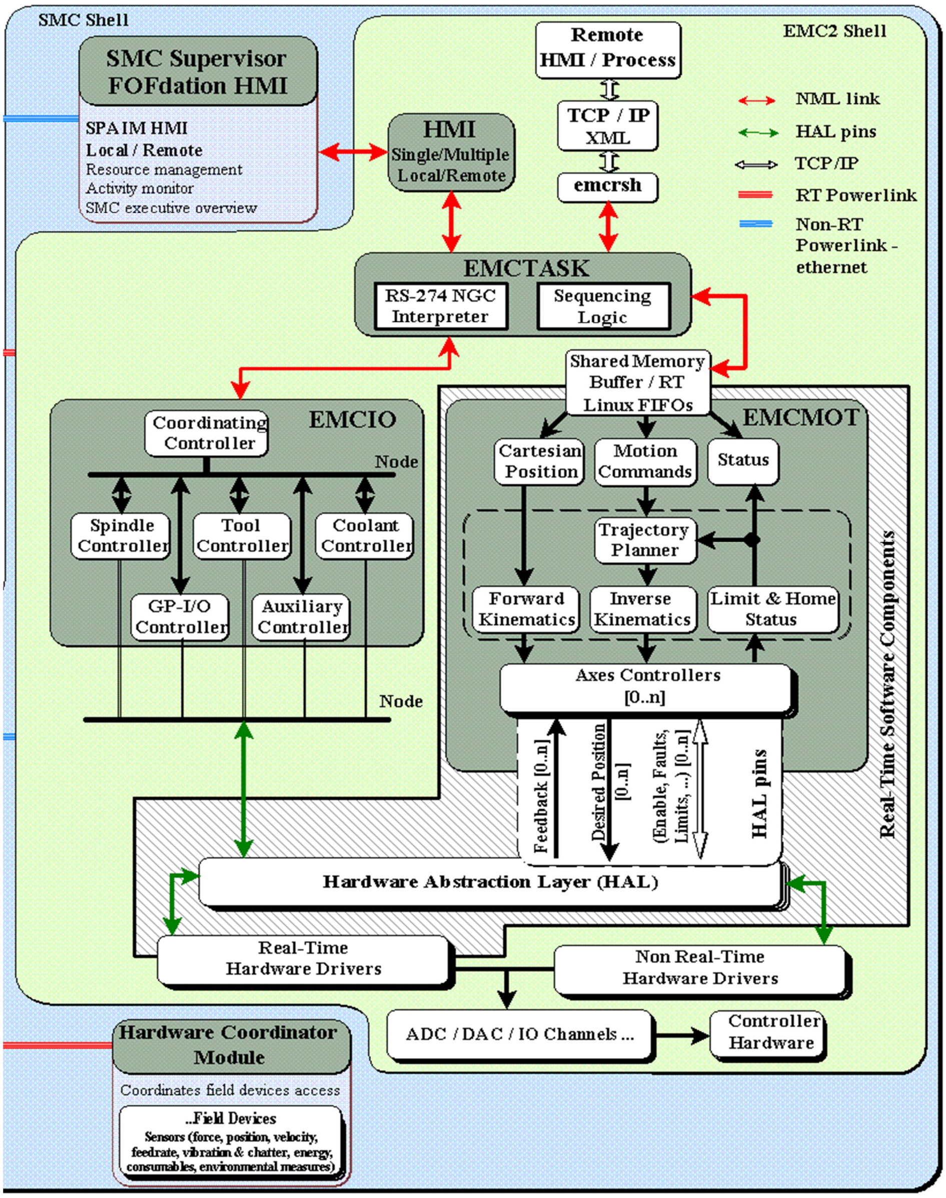

Fig. 5. Open CNC manufacturing system implemented at IRCCyN

A primary benefit of this ITP is that since the core of the tool path interpolator is open on the LinuxCNC side, it can be updated to be able to directly control Nurbs or B-splines, to work with the process planner to update the workplan, or to propose new tool path parameterizations to optimize the process according to the machine behavior which can be predicted. The platform has been already tested by milling test parts such as STEP-NC Fishhead part and the Butterfly Nurbs from the LinuxCNC community (Fig. 5).

Hence, the implementation of the online tool path compensation method proposed in this paper would be implemented very efficiently due to the accessibility of the open interpolation kernel. Real time modification of the tool paths control points could be adapted to the machine tool specificities.

5. CONCLUSION

Tool path generation and control is a central issue in CNC manufacturing as it has to adapt to the actual geometry of the workpiece. In this paper, a strategy based on online measurements is presented. It enables an adjustment of the tool path during the manufacturing operation and confers more flexibility to the traditional and relatively limited CNC tool path programming. For this purpose, closed-loop machining is implemented and comprises three main ingredients: a CNC machine tool, a measurement device and a data-processing algorithm. Data is acquired online and processed in real-time in order to steer the tool path and to improve the conformity of the part.

A first feasibility study conducted on a practical case is conclusive. The method proves to be repeatable which makes it well suited to the industrial framework.

Further developments will be done to implement this method on open NC controllers in order to dramatically increase its efficiency, by acting directly on the tool path interpolator itself.

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