

## **Computer Aided Engineering**

## A haptic approach to computer aided process planning

C.A.Fletcher<sup>1</sup>, J.M.Ritchie<sup>1</sup> and T.Lim<sup>1</sup>

<sup>1</sup> School of Engineering & Physical Sciences, Heriot Watt University, UK

**Abstract.** Current solutions in Computer Aided Process Planning (CAPP) can be time consuming, complex and costly to employ and still require the input of an experienced planner. Implementations can require a high degree of configuration, particularly when pre-existing knowledge within the company needs to be incorporated. This means due to the time and expense many companies, particularly smaller ones, do not employ CAPP systems. Within the process planning domain of machining, decisions need to be made regarding routing and processes, with each choice making a significant impact on the final cost and quality of the product. Existing CAPP systems need to be carefully configured as they rely on artificial intelligence or existing data to find the best routes and processes. These systems tend to be very specialised and their configuration can be tedious. This paper presents a prototype haptic virtual machining application where machining operations are simulated whilst visual and tactile information is fed back to the operator to enhance their experience. As they generate their machining sequence the operator input is logged. By logging their activities it is shown that specialist knowledge can be accumulated unobtrusively and formalised such that the system can immediately generate usable process plans without the need for lengthy configuration and formalisation. Experimental findings show how using a virtual reality (VR) environment can clearly represent a machining task and that relevant knowledge and data can be quickly captured during a simulation. Simulating machining tasks in this way offers a unique non-intrusive opportunity to collect important information relevant to a machining process; this information can then be used further downstream during manufacturing.

**Keywords:** CAPP, haptics, virtual environment, process planning

### 1. Introduction

Computer Aided Process Planning is the link between Computer Aided Design and manufacturing. A process plan comprises the selection and sequence of operations and associated processes to transform a chosen raw material into a finished product [1]. A plan includes routing sheets, operation lists and tool lists which detail machining operations, machine scheduling and tooling requirements.

Traditionally process plans were carried out by a senior engineer and by combining their expertise with the part requirements a process plan would be generated that could then be passed to the shop floor for

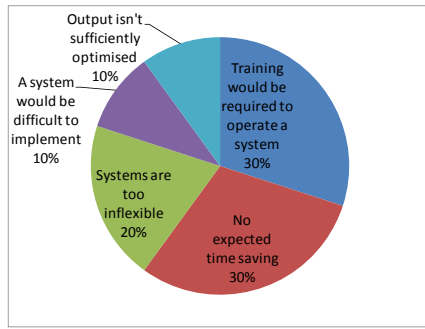
manufacture. The problem with plans generated this way is that they suffer from excessive clerical content, lack consistency and are dependent on the knowledge and experience of the planner.

Early evolutions of PC software aimed at addressing these problems were variant CAPP systems. A variant CAPP system is knowledge based system, which draws from previous designs to generate new or partial plans, through the use of a classification code [2]. These plans can then be taken as a base line by the process planner for further refinement into the final plan.

The next evolutions of CAPP systems were termed generative. These are based on artificial intelligence algorithms to automatically create unique plans for each new design. The intention was to create a fully automated process plan generated directly from the design files. This would allow a fast and seamless transition direct to manufacturing. However, these plans invariably needed to be finished off via some manual input, or would be limited to a very specific part family of components. A further review of papers written from 2009 onwards reveals that much of the research is still focused on trying to create automated systems [3-6], are based on feature recognition [7-9] are knowledge based systems [10,11] are based on a genetic algorithms.

In spite of these extensive research efforts, the uptake of automated CAPP systems into industry has been slow [12] and they tend not to be used in small to medium enterprises (SMEs) at all [13]. With considerable potential savings.

A short survey of 19 SMEs (Fig. 1 Survey of reasons for non implementation of CAPP systems) indicated some of the reasons for CAPP systems not being used: (i) there is no expected time saving; (ii) they require considerable training; and (iii) the final results are not always optimal.



**Fig. 1** Survey of reasons for non implementation of CAPP systems

In order to address some of these issues this paper proposes a different approach using a novel virtual reality (VR) paradigm to create a simulated machining environment via haptic routing. In this environment operators will be able to generate the cutting sequence and simulate the machining of a part in real time. Whilst the part is being machined relevant information is automatically logged and used to generate a unique process plan.

Virtual reality can be defined as the creation in software of a real world situation [14]. The benefits a virtual environment can bring to the human experience include: (i) the ability to rapidly prototype different solutions; (ii) a better understanding of problems through improved visualization; and (iii) more collaborative approaches due to the ability to share complex information more easily.

Central to this application is the inclusion of a haptic device. This is an electro-mechanical device which introduces a sense of feel into the virtual environment allowing the operator to interact with models in a more natural way [15]. The phantom omni haptic device by Sensable was used in this instance since the movements required for simulating routing cutting operations are similar to several types of part programming and planning approaches used in a typical workshop. By creating an abstract simulation of a machining environment, it is thought that a semi-automated process planning tool can be developed; which will give the process planner the support that is needed, to quickly and efficiently evaluate cutting sequences, and automatically generate plans. The latter feature addresses the issues found in traditional process planning by removing excessive clerical content and the lack of plan consistency. Further, because the system uses a virtual environment similar to a machining environment it should be intuitive and allow the development of highly optimized easily editable solutions. Indeed, the virtual system aims to integrate the intelligence of the process planner and the haptic interface by allowing the human to be immersed in, and experience the process rather than being involved in post editing.

This paper presents a pilot study of a virtual haptic machining application, addressing whether or not a

virtual haptic approach can be used to generate plans more efficiently than in the traditional manner. After an initial explanation of the system implementation, the experimental method is explained followed by a short discussion of results, conclusions and future work.

## 2. Implementation

The virtual environment (Fig. 2. Virtual Environment including Haptic Device) consists of commercially available hardware and an in-house developed software application.

The hardware includes a Sensable Phantom Omni haptic device and a Dell T1500 Workstation, which includes an INTEL CORE I5-750(2.66GH) CPU, 4GB 1333MHZ DDR3 RAM, NVIDIA Quadro FX580 GPU.

The software consists of a multi-threaded application, comprising of a graphical interface, models with physical attributes and a haptic module to provide sensory feedback. The haptic application requires 1 kHz rendering frequency to reproduce forces convincingly. Software libraries used include OpenSceneGraph, ODE, osgModelling, OpenHaptics [16, 17, 18, 19].



**Fig. 2.** Virtual Environment including Haptic Device

The graphical interface shows a virtual machine table, a selection of tools including drills, end mills, clamps and an inspection probe. The operator can pick up and manipulate the billet, clamp it and then carry out milling and drilling operations based on a routing methodology similar to existing CAD/CAM packages. Meanwhile, in the background, the object being manipulated – such as a cutting tool – is logged and monitored, its position, velocity and virtual cutting force captured. This data is recorded in a text file (Fig. 3 Sample of Logged data.) which is then post-processed to automatically generate routing, operation and tool list sheets (Fig. 4 Sample of data from generated route plan.) the reasoning for which is automatically inferred from the interactive haptic cutting sequence activities.

Time	Tool	L_Position(x)	L_Position(y)	L_Position(z)
1	Start			
5267	Billet	-111.5	6.212	3.954
46886	Billet	-111.5	6.212	3.953
88630	Billet	-111.5	6.211	3.955
132791	Billet	-111.5	6.21	3.958
176890	Billet	-111.5	6.207	3.963
219134	Billet	-111.5	6.203	3.971

Fig. 3. Sample of logged data.

Operation List					
Operation Number	Description	Machine Tool	Tooling	Stop PosX	Stop PosY
10	Move Billet			-0.2747	0.4444
20	Clamp A			-0.04591	0.2923
20	Drill	Drilling Station	Drill 5mm	-0.6301	-0.07457
30	Drill	Drilling Station	Drill 10mm	-0.6199	-0.09375

Fig. 4. Sample of data from generated route plan.

### 3. Experimental method

Six test subjects comprising of a mixture of novice and intermediate process planners were asked to carry out two process planning tasks in a random order, one task was to be carried out in a traditional manner (Task 1) and the other using the haptic virtual environment (Task 2).

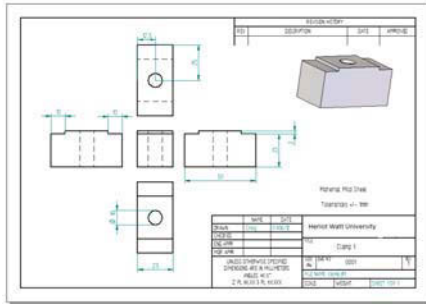


Fig. 5. Clamp

For Task 1 the test subject was presented with a mechanical drawing of a clamp (Fig. 5 Clamp), paper templates for routing sheets, operations lists and tool lists and photographs with descriptions of the tools available to them in the workshop. The tools included a pillar drill, a milling machine, a work bench and a clamp. The tooling family comprised two drill bits of 5mm and 10mm diameter and a 16mm end mill. The test subject was then asked to generate a process plan using the resources available and the task timed.

For task 2 the test subject was requested to simulate the machining of the same object in the virtual environment and told all the information would be automatically logged in order to generate the process plan automatically. The test subject was given around 10

minutes to become accustomed to the environment before beginning the task. The time taken to complete the second task was also timed.

### 4. Experimental results

The Task Completion Time (TCT) for Task1( blue) and Task 2 ( red) for each test subject are shown in Fig. 6 Time to complete process plan.. Trend lines have been added to each set of results for clarity.

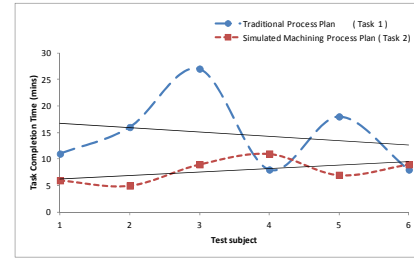


Fig. 6. Time to complete process plan.

The TCT has been plotted against the Plan Data Quality (PDQ) in Fig. 7. Process plan completion time and quality. PDQ is expressed as a % compared to a correct plan. The experience of the test subject is also highlighted in different colours. Operator experience was defined as follows: (i) a novice has no mechanical engineering background; (ii) the intermediate level has a mechanical background and some process planning training; and (iii) the expert level carries out process planning on a daily basis. The TCT and PDQ of the process plans generated by Task 2 are plotted in purple for comparison to Task 1.

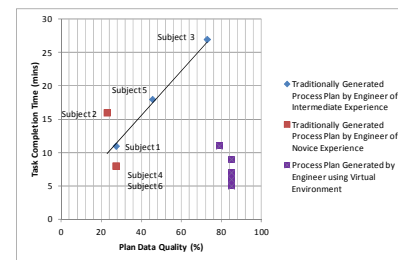


Fig. 7. Process plan completion time and quality.

Figure 8 shows examples of plans automatically generated by the virtual environment and those generated in a traditional manner.

### 5. Discussion of results

It can be seen from Figure 6 Time to complete process plan that 66.6% of the users developed a process plan in the virtual environment more quickly than in a traditional

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## 6. Conclusion and future work

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## Integrated tactile-optical coordinate system for the reverse engineering of complex geometry

F. Li, A. P. Longstaff, S. Fletcher and A. Myers

Centre for Precision Technologies, School of Computing and Engineering, University of Huddersfield  
Queensgate, Huddersfield, HD1 3DH, UK.

**Abstract.** To meet the requirement of both high speed and high accuracy 3D measurement for reverse engineering of artefacts, an integrated contact-optical coordinate measuring system is proposed in this paper. It combines the accuracy of contact measurement using a co-ordinate measuring machine (CMM) and the efficiency of full field of structured light optical scanning methods using a projector and two CCD cameras. A planar target printed with square patterns is adopted to calibrate the projector and cameras while three calibration balls are used to unify two coordinate systems. The measurement process starts from cameras around the volume to capture its entire surface, then the CMM's probe is used to re-measure areas of the object that have not been adequately scanned. Finally the combined data from both systems is unified into the same coordinate system. In this paper the hybrid measurement of a guitar body proves the feasibility of this method.

**Keywords:** Integrated system, Structured light measuring, CMM, 3D measurement, Data fusion

### 1. Introduction

In recent years, extensive attention has been given to different methodologies of reverse engineering (RE) aimed at developing more effective measurement methods which provide both high speed and high accuracy. The existing CMM methods are widely used for industrial dimensional metrology, but the digitisation process is very time-consuming for the acquisition of the first set of points on complex, freeform surfaces. An alternative approach is represented by non-contact digitisation of surfaces based on optical techniques, such as time-of-flight lasers [1], laser scanning [2, 3], stereovision [4] and structured light [5]. These optical instruments can efficiently capture dense point clouds in terms of speed and reduces the human labour required. However it is usually difficult for the optical sensors to digitize the non-surface objects, such as slots or holes, due to occlusions and obscuration of these artefacts.

The reduction of the lead time in RE, and the increased requirements in term of flexibility as well as accuracy have resulted in a great deal of research effort aimed at developing and implementing combined systems for the RE based on cooperative integration of in homogeneous sensors such as mechanical probes and optical systems [6-9]. Particular features of a workpiece can be measured with the most suitable sensor, and these measurements with low uncertainty can be used to correct data from other sensors which exhibit systematic errors but have a wider field of view or application range.

However, a limitation of the proposed systems is that the integration of the optical system with the CMM generally takes place but is limited at the physical level, flexibility level and usability level [7, 8]. This paper describes a flexible and effective approach for the integration of a 3D structured light system with dual CCD cameras and a CMM to perform the reverse engineering of freeform surfaces. The system does not need the physical integration of the two sensors onto the CMM, but includes their combination at the measurement information level. The aim is to measure a wider range of objects of complex geometry rapidly with higher accuracy than any individual measurement system alone. The structured light sensors are applied to scan the profile of a part from different views, while the trigger probe is used to measure key features, the edge and blind area of the structured light sensor on a part. The limitations of each system are compensated by the other and measurement results from all of the optical sensors and the CMM probe head are combined into one set. The main characteristics of the methodology are given in the following sections.

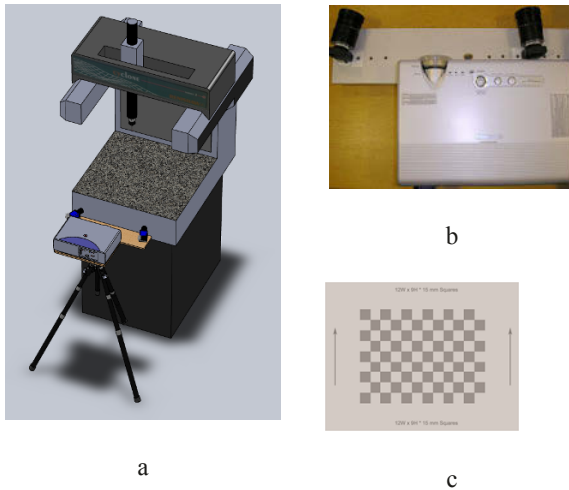


## 2. System configuration

### 2.1. Elements of the integrated system

The integrated system [see Fig. 1 (a)] is designed and manufactured with the following components:

- Two CCD cameras: IDS UI-1485LE-M-GL, the CCD array resolution is 2560(H) x 1920(V), the dimension of a pixel on CCD array is  $2.2\mu\text{m} \times 2.2\mu\text{m}$  [see Fig. 1 (b)].
- Lens: Fujinon HF12,5SA-1/1,4 5 Megapixel C-Mount Lens, the focal length is 12.5 mm.
- Projector: Panasonic PT-LB60NTEA projector with 1,024 x 768 pixels.
- Co-ordinate measuring machine (CMM): Renishaw cyclone.
- FlexScan3D PRO 3D scanning software.
- Calibration board [12W x 9H x 15 mm Squares, see Fig.1 (c)] for optical scanner calibration and three calibration balls (nominal diameter 52 mm).
- PC Workstation.



**Fig. 1.** Elements of the integrated system a. the integrated system; b. cameras and projector ; c. calibration board

### 2.2. The principle of optical system

The optical system is based on the structured light measurement technique [10-14] with digital sinusoidal fringe and Gray code projection and consists of a digital projector and two CCD cameras that provide redundancy to reduce the effect of obstructions and improve accuracy.

The measurement process is performed in three steps: Generation of stripe patterns, phase measurement (based on the analysis of deformed stripe patterns) and calibration of the phase values in each

pixel of the camera to the real-world (x, y, z) Cartesian coordinates.

## 3. Measurement process of the integrated system

### 3.1. Calibration of the optical system

There are many studies of modelling and calibration of CCD cameras. Camera calibration in the context of 3D optical measurements is the process of determining the transformation from 2D CCD image to 3D world coordinate system. The parameters to be calibrated include intrinsic parameters and extrinsic parameters. The intrinsic parameters involve: (1) effective focal length -the distance between the projection centre and the image plane, (2) principle point-the intersection of the optical axis and the image plane, (3) lens distortion and (4) aspect ratio-the length-width ratio of each pixel. The extrinsic parameters involve the transformations between the world coordinate system, the camera coordinate system and the image coordinate system. Extrinsic parameters are needed to transform object coordinates to a camera-centred coordinate system. In many cases the overall performance of a machine vision system strongly depends on the accuracy of the camera calibration procedure [15-19]. To solve all of the intrinsic and extrinsic parameters simultaneously, at least six non-coplanar points in the world coordinate system and their correspondences on the image are required. Zhang [20] proposed a flexible technique for camera calibration by viewing a plane from different unknown orientations. Accurate calibration points can be easily obtained using this method.

### 3.2. Data fusion of integrated system

Multisensor data fusion in dimensional metrology can be defined as the process of combining data from several information sources (sensors) into a common representational format in order that the metrological evaluation can benefit from all available sensor information and data [9]. The optical scanner and the CMM work in their own separate coordinate systems. If the integrated system is to produce useable results, these two coordinate systems have to be unified.

Coordinate transformation of 3D graphics includes geometric transformations of translation, proportion, rotation and shear. In this first step, the multi-sensor data fusion in this paper assumes no systematic measurement error and only involves translation and rotation transformation. Optical scanner and CMM data fusion can therefore be seen as a rigid body transformation. Since three points can express a

complete coordinate frame, data transformation in two systems will be achieved simply with three different reference points and a three-point alignment coordinate transformation method can be used to deal with data fusion.

Since the error of each measuring reference point can be seen as equal weight value, the data fusion errors can be seen as average distributed errors [21]. It is usually very difficult to obtain the same reference point from two different sensors (CCD cameras and CMM in this case) because of different measurement principles and methods of two systems as well as different point cloud density. If we take a reference feature point as the calibration reference point every time, the possibility of occurrence of system error, human errors and accidental errors will increase greatly. Because three points can establish a coordinate, we can calculate the centroid of a standard calibration ball and then use the sphere centre coordinate as the datum reference point coordinate to achieve data fusion and reduce fusion errors. The data fusion of 3D measurement data from different systems will be achieved through the alignment of three datum sphere centre points. In fact, the data fusion problem is, therefore, converted to a coordinate transformation problem. The transformation is determined by comparing the calculated coordinates of the centres of the calibration balls obtained in measurement conducted by the optical system [8]:

$$W_{CMM} = R \cdot W_s + T \quad (1)$$

where  $W_{CMM}$  is the points' coordinates in CMM alignment;  $R$  is the rotation matrix;  $W_s$  is the point's coordinates in optical alignment; and  $T$  is the translation vector.

Specific methods are as follows:

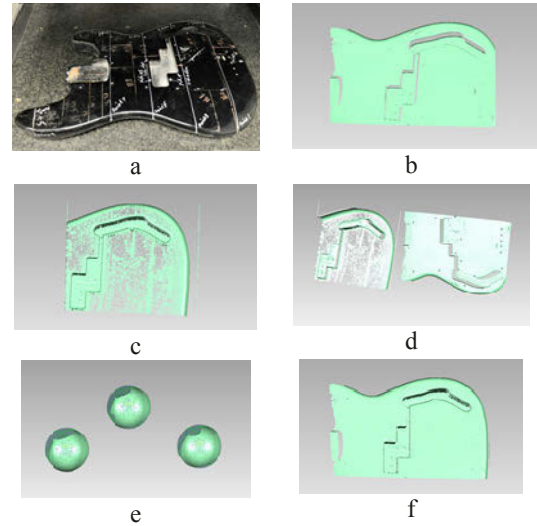
- Calibrate the optical system (section 3.1).
- Use CMM to measure the surfaces of three standard balls.
- Use structured light scanner to measure the surfaces of the same standard balls.
- Use optical scanner and CMM measure the workpieces separately.
- Calculate the sphere centre coordinates measured in two systems and use the sphere centre as reference points to achieve data fusion.

This measuring ball operation has to be performed prior to any measurement, after the calibration of the optical system. It is carried out only once before a series of measurements. Change of configuration of any of systems results in the need of repeating the unification process. The result of this process is a

transformation matrix, which modifies (rotates and translates) the point's coordinates from the optical scanners' relative coordinate system to the absolute system of the CMM.

#### 4. Experimental results

After building the integrated system, an electrical guitar body [see Fig. 2(a)] has been used to demonstrate the feasibility of the proposed method. The surface of guitar body includes a freeform surface and a pick-up slot which is difficult to measure for an optical scanner because of occlusions and obscuration of artefacts. Therefore we can use optical scanner to capture the freeform surface 3D data of guitar body then digitize the pick-up slot surface by using the CMM.



**Fig. 2.** Guitar body points cloud data coordinate system unification a. optical scanner measurement; b. data measured by optical scanner; c. data measured by CMM; d. data measured by two systems; e. calculation of ball sphere centre; f. data fusion of two systems.

Specific steps are as follows:

- Calibrate the optical scanner by using a calibration board, then use both CMM and optical scanner to measure three calibration balls mounted on the CMM granite bed.
- Use structured light scanner to capture dense point clouds data of freeform surface efficiently [see Fig. 2(b)]. However the cameras cannot capture the surface information of pick-up slot because of ambient occlusion and obscuration of guitar surface, and then we use CMM's contact head to re-measure the slot area that has not been registered [see Fig. 2(c)]. As the scanning



speed of structured light scanner is very fast (An average scan takes between 1 to 6 seconds), while a CMM only needs to digitize the slot surface, compared to performing a full surface measurement by using a CMM alone, the data acquisition speed of the integrated system improves greatly. In this example, the CMM-contact digitisation of one guitar surface need more than 8 hours, while the hybrid system can finish the measurement within one hour. The point cloud data obtained in both systems [Fig. 2 (d)].

- Calculate the sphere centre coordinates calibration balls measured in two systems [see Fig. 2 (e)].
- Use the sphere centre coordinates to unify the two coordinate systems, the unified guitar point clouds data as shown in Fig. 2 (f).

## 5. Conclusions and discussions

To meet the requirement of measuring complex geometry of workpieces with high accuracy and speed, a full field of integrated scanning system, which mainly consists of a CMM, two CCD cameras and a DLP based standard projector, has been developed in this paper. The unification of contact and non-contact systems are fulfilled by using three calibration balls mounted on a CMM granite bed. The hybrid measurement of guitar body showed this approach is simple, convenient, efficient and reliable. However, in this paper we do not verify the accuracy of the integrated system. No visual separation between the data sets from different measuring systems indicates a fit accuracy within 0.5 mm, proving the feasibility of this approach. Theoretically, the integrated system accuracy and resolution depend on both separate systems, but should be biased towards the contact method, and can be improved by improving the specifications of hardware, including choosing a higher accuracy CMM, choosing more precise calibration balls and a higher resolution projector which can provide sharper stripe. Reducing the measuring range can also improve the system accuracy. Further research will include more extensive experiments to test the accuracy of the integrated system and more sophisticated design of the algorithm to reduce the manual intervention.

**Acknowledgements:** The authors gratefully acknowledge the UK's Engineering and Physical Sciences Research Council (EPSRC) funding, of the Centre for Advanced Metrology under its innovative manufacturing program.

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## Adapting STEP-NC programs for interoperability between different CNC technologies

M. Safaieh, A. Nassehi and S. T. Newman  
Department of Mechanical Engineering, University of Bath

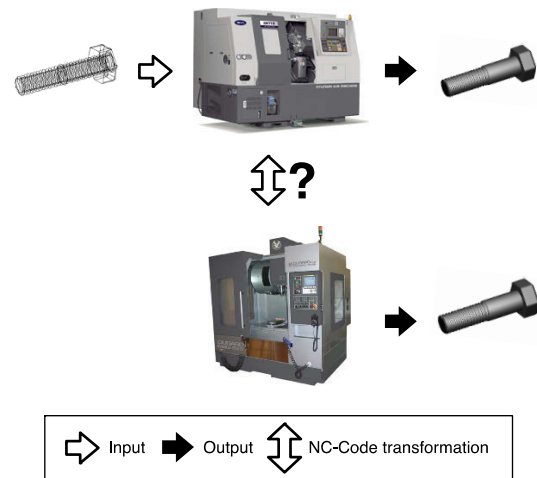
**Abstract.** Since the 1990s, complex multi-axis and multi-process machines with complex controllers have been commonplace for the efficient batch production of precision parts that incorporate various technologies such as milling, turning, grinding and laser cutting. With this level of complexity, interoperability between different resources and technologies in CNC metal cutting machines has always been difficult. For dealing with this difficulty in interoperability, researchers started to identify an efficient way of realising interoperability between CNC machine tools with different technologies for machining the same component on various CNC machines. STEP-NC is a rich information standard developed to replace the traditional programming languages used for CNC machines. The aim of this paper is to propose a methodology based on the use of STEP-NC to develop a framework for cross technology interoperability. A prototype implementation of the framework is tested by converting a STEP-NC programme written for a 4-Axis milling machine to one suitable for a turn-mill machine.

**Keywords:** Interoperability, CNC machining, STEP-NC

### 1. Introduction

In the 21st century, CNC machines with advanced technological capabilities have become the state-of-the-art tools for manufacturing complex parts with tight tolerances. Due to the availability of CNC machines with different technologies, it has become possible to produce complex products with high speed and high precision [1, 2]. To fully enable interoperability, it is essential to have a system, which is not dependent on a machining process. This is because by having such a system, generating NC codes for different CNC machines will be based on manufacturing information not just the machining process [3]. Due to the development of CNC machines with multiple axes and capability of carrying out multiple processes, interoperability between these machines has become a challenging issue for researchers with the aim of finding the way for communication between these machines without the necessity for human resources. As illustrated in Fig.1, machining a part with two CNC machines with different technologies without the need

for an expert to generate the code is still a gap in interoperability.



**Fig. 1.** Machining a part with two CNC machines with different technology

To solve this problem, the authors have designed a system to read G&M codes as a source code from one machine and analyse the necessary information for generating NC code for another machine [3]. The aim for this paper is to enhance the system by identifying the elements in a STEP-NC code and importing them to the intelligent translator to generate a STEP-NC code for another CNC machine with a different technology (destination machine).

### 2. Background

Interoperability in manufacturing using CNC machines has been a major area of research over the last 10 years [4]. In 2007, Nassehi presented the barriers and issues of incompatibility between the various CAD/CAM/CNC

systems and proposed a new framework to overcome these barriers in achieving interoperability in the CAD/CAM/CNC chain [5]. Newman provided a strategic view of how interoperability can be implemented across the CAx chain with the range of standards used to regulate the flow of information [1]. Yusef described and illustrated a STEP compliant CAD/CAPP/CAM system for the manufacturing of rotational parts on CNC turning centres [2]. In 2010, Zhang developed a new software tool to demonstrate the feasibility of interoperable CNC manufacturing based on STEP-NC [6].

STEP-NC (ISO 14649) defines methods for incorporation of a variety of production information in a new type part program which is different from G&M code based on axis movement [7].

The authors proposed the framework for a new translator to allow G&M codes to be translated from one technology to another [3]. In the framework as illustrated in Fig. 2, the adapter read a series of G-codes from the source machine and analyses the imported information for generating new code for a destination machine [8].

The adapter itself communicates with two databases: First the “Manufacturing Dictionary” which consists of machine reference information, cutting tool reference information, operation meta-data, feature meta-data and CNC STEP-NC meta-data. Second the “Manufacturing Process Database” consists of cutting tool information, manufacturing feature information and machining operation information.

The adapter itself consists of three major elements: A Reader, which imports the code. An Analyser, which analyses the imported information for generating a new code, And A Writer, which generates the STEP-NC code based on the information provided by the analyser.

### 3. Methods

In this paper the framework in Fig. 2 is extended to use STEP-NC as input from the source to generate new code for the destination machine.

STEP-NC code consists of general information such as filename, author, date and organization, and detailed information such as working steps, work plans, machining operations, manufacturing features and their geometry.

The role of the reader is to identify the tools, features and operation in the source machine STEP-NC code and store them in the manufacturing process data-base.

As illustrated in Fig. 3, the reader will identify the machining working steps and form the information in the machine working step determining manufacturing feature and machining operation.

Tools and technology information will be determined from machining operation and feature geometry from manufacturing features, after identifying the information for the adapter the reader will store all the information to the manufacturing process data-base.

The analyser in the adapter will process the data in the manufacturing process data-base based on information in the manufacturing dictionary and then the writer will generate the STEP-NC code for the destination machine.

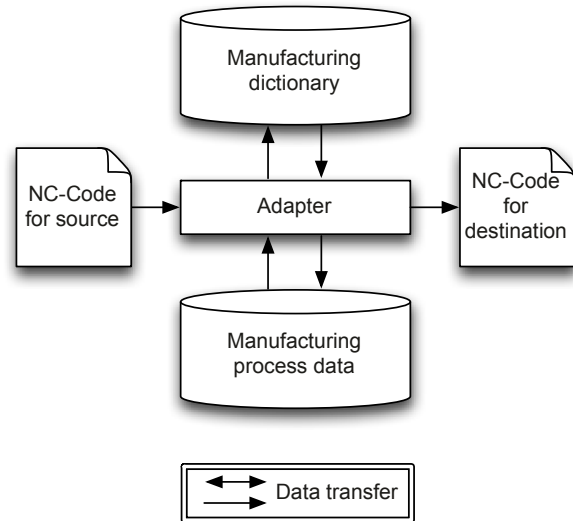


Fig. 2. Framework for information flow in the CNC machining chain

The method used in the analyser is converting machining operation and machining features information from source to destination based on the availability of tools and operations in the destination machine.

To realise such a system, the analyser should categorise the machining operations and features to different sublevels and then start to find the operations and features from the manufacturing process database that are suitable for the destination CNC machine based on the source machining information.

As illustrated in Fig. 4, the writer starts to read the destination machine information from the Manufacturing Dictionary for generating the Header and Data section of STEP-NC file. The information for the header is similar to the information of the source machine. For data section the writer reads the first operation from manufacturing process data-base, (which is carried from analyser decision) and then reads the feature (which is chosen for the current operation).

After reading the operation and the feature, the writer will generate the code based on information in manufacturing dictionary and write the STEP-NC code to a file. The writer finishes the process at the last operation.

For testing the system, a part with milling and turning features has been chosen. The part consists of five different features: Planar Face, Profile Feature, Step, Closed Pocket and Slot. Which can be machined with two operations: Planer\_milling and Bottom\_and\_side\_milling? This information will be identified from the input

code. An excerpt of the input programme is shown in Table 1.

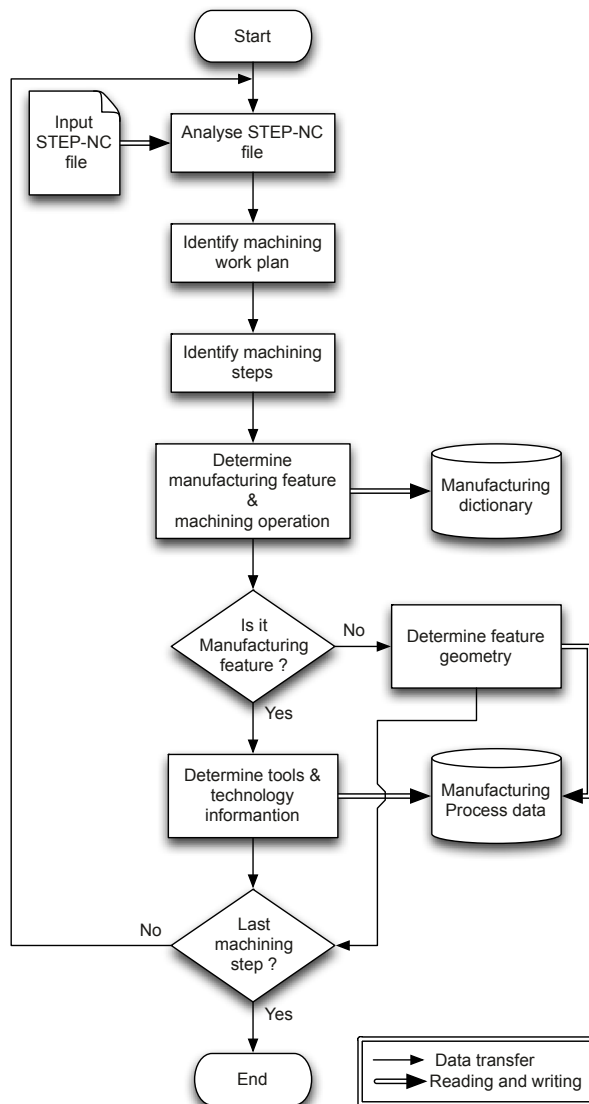


Fig. 3. Reader process flowchart

This programme was fed into the adapter in order to obtain a turn-mill programme to machine the same component. The header of the new programme will be similar to the source and for the data; features and operations are the most codes, which are changing during the conversion. Table 2 illustrates the new STEP-NC code for the destination machine with the differences highlighted. Machining the part on both machines produced identical results.

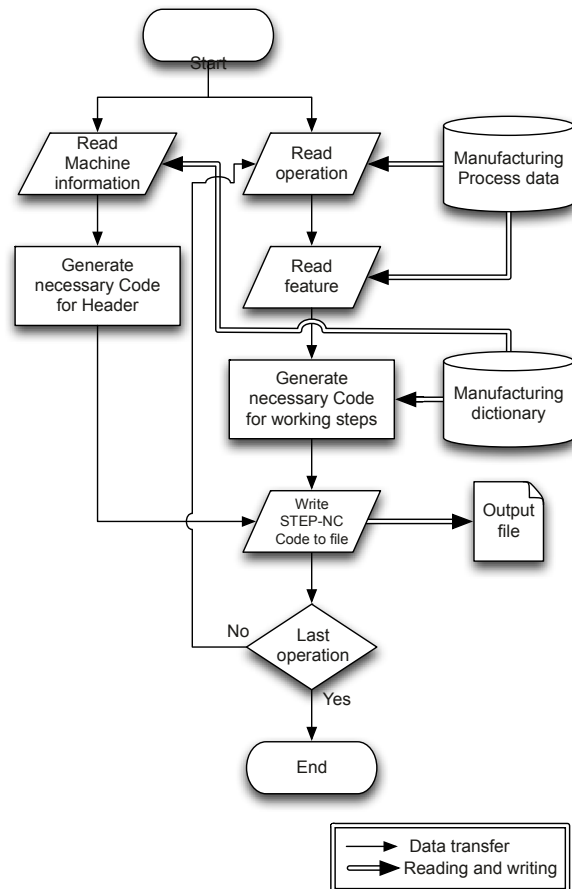


Fig. 4. Writer process flowchart

Figure 5 illustrates the part with five features. For testing the experimental part a 4 axis CNC milling machine and a C-axis turn-mill machine were chosen.



Fig. 5. Experimental part



**Table 1.** An excerpt of the STEP-NC milling programme written to machine the component

<pre> DATA; #1= PROJECT('MATADOR CASESTUDY',#2,(#4),\$,\$,\$); #2= WORKPLAN('MAIN WORKPLAN',(#10,#11,#12,#13,#14,#15,#16,#17,#18,#19,#20,#21,#22,#23, #24,#25),\$,\$,#8,\$); #4= WORKPIECE('SIMPLE WORKPIECE',#6,0.010,\$,\$,\$,(#66,#67,#68,#69)); #6= MATERIAL('ST-50','STEEL',(#7)); #7= PROPERTY_PARAMETER('E=200000N/M2'); #8= SETUP('SETUP1',#71,#62,(#9)); #9= WORKPIECE_SETUP(#4,#74,\$,\$,()); </pre>	WORKPIECE DEFINITION
<pre> #10= MACHINING_WORKINGSTEP('ROUGH PLANAR FACE',#62,#30,#40,\$); #11= MACHINING_WORKINGSTEP('FINISH PLANAR FACE',#62,#30,#41,\$); #12= MACHINING_WORKINGSTEP('ROUGH PROFILE',#62,#31,#42,\$); #13= MACHINING_WORKINGSTEP('FINISH PROFILE',#62,#31,#43,\$); #14= MACHINING_WORKINGSTEP('ROUGH STEP',#62,#32,#42,\$); #15= MACHINING_WORKINGSTEP('FINISH STEP',#62,#32,#43,\$); #22= MACHINING_WORKINGSTEP('ROUGH POCKET',#62,#33,#42,\$); #23= MACHINING_WORKINGSTEP('FINISH POCKET',#62,#33,#43,\$); #24= MACHINING_WORKINGSTEP('ROUGH SLOT',#62,#34,#42,\$); #25= MACHINING_WORKINGSTEP('FINISH SLOT',#62,#34,#43,\$); </pre>	WORKING STEPS
<pre> #30= PLANAR_FACE('PLANAR_FACE1',#4,(#40,#41),#70,#63,#24,#25,\$,()); #31= PROFILE_FEATURE('PROFILE',#4,(#42,#43),#71,#63,#24,#25,\$,()); #32= STEP('STEP',#4,(#42,#43),#72,#63,#24,#25,\$,()); #33= CLOSED_POCKET('POCKET',#4,(#42,#43),#73,#63,#24,#25,\$,()); #34= SLOT('SLOT',#4,(#42,#43),#74,#63,#24,#25,\$,()); </pre>	FEATURES
<pre> #40= PLANE_ROUGH_MILLING(\$,\$,'ROUGH PLANAR FACE',10.000,\$,\$39,#40,#41,\$,\$,#60,#61,#42,2.500,\$); #41= PLANE_FINISH_MILLING(\$,\$,'FINISH PLANAR FACE',10.000,\$,\$39,#40,#41,\$,\$,#60,#61,#42,2.500,\$); #42= BOTTOM_AND_SIDE_ROUGH_MILLING(\$,\$,'ROUGH POCKET1',15.000,\$,\$39,#50,#41,\$,\$,\$51,2.500,5.000,1.000,0.500); #43= BOTTOM_AND_SIDE_FINISH_MILLING(\$,\$,'FINISH POCKET1',15.000,\$,\$39,#52,\$41,\$,\$,\$53,2.000,10.000,\$,\$); </pre>	OPERATIONS

#### 4. Conclusion and future works

This paper reviewed the interoperability in manufacturing and standards in interoperability. The major contribution of the paper is the use of ISO14649 (STEP-NC) in a cross technology environment to realise an interoperable system. This system allows a part to be manufactured without dependency on a specific process or resources with two CNC machine centre with very different technologies; provided that they both have the capability to make the part. The future work will be focused on extending the framework to work with more CNC machines with a wider variety of technologies at the same time and also more complex part with additional features.

**Table 2.** An excerpt of the STEP-NC turn-mill programme written to machine the same component

<pre> DATA; #10= MACHINING_WORKINGSTEP('ROUGH FACE',#62,#30,#40,\$); #11= MACHINING_WORKINGSTEP('FINISH FACE',#62,#30,#41,\$); #12= MACHINING_WORKINGSTEP('ROUGH PROFILE',#62,#31,#42,\$); </pre>	WORKING STEPS
<pre> #30= REVOLVED_FLAT('FACE',#4,(#40,#41),#70,#63,#24,#25,\$,()); #31= GENERAL_REVOLUTION('PROFILE',#4,(#42,#43),#70,#63,#24,#25,\$,()); </pre>	FEATURES
<pre> #40= FACING_ROUGH(\$,\$,'ROUGH FACE',10.000,\$,\$39,#50,#51,\$, #60,#61,#42,2.500,\$); #41= FACING_FINISH(\$,\$,'FINISH FACE',10.000,\$,\$39,#50,#51,\$, #60,#61,#42,2.500,\$); #42= CONTOURING_ROUGH(\$,\$,'ROUGH PROFILE',10.000,\$,\$39,#52,#53,\$, #60,#61,#42,2.500,\$); </pre>	OPERATIONS

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## A heuristic approach for nesting of 2D shapes

Gianpaolo Savio<sup>1,2</sup>, Roberto Meneghello<sup>2</sup> and Gianmaria Concheri<sup>2</sup>

<sup>1</sup> ENDIF (ENgineering Department In Ferrara) - University of Ferrara - Via Saragat, 1 - 44100 - Ferrara - Italy

<sup>2</sup> DICEA-Lin (Laboratory of Design Tools and Methods in Industrial Engineering) - University of Padova - Via Venezia, 1 - 35131 - Padova - Italy

**Abstract.** In several manufacturing processes, the cutting of 2D parts from sheets is an important task. The arrangement of the parts in the sheets, supported by computers, is called nesting and is addressed to minimize the wasted material. In literature some approaches are proposed, based on genetic or heuristic algorithms which emphasize different characteristics, e. g. the time complexity or the wasted material. In shipbuilding the parts to be arranged have significantly different sizes, which are often difficult to pack in a fast way using the standard methods in literature. In this work an approach is proposed, able to arrange parts with very different dimensions, which is based on the identification of a suitable starting rotation that ensures a solution in a reasonable time. The main steps are: a) importation of the model files of the parts to be packed, b) identification of a preliminary orientation and sorting of the parts (starting position), c) optimization of the position of the parts, ensuring a minimum distance between them. For the starting rotation, three different orientations are considered: i) the original orientation, ii) the x axis coincident with the minimum inertia axis, iii) the x axis aligned with the maximum edge. The orientation is selected in order to obtain the minimum area of the bounding box. The implementation of the method has been investigated and the results show the advantages of the approach: reduction of waste material and time for performing the nesting.

**Keywords:** CAD/CAM, CAPP, Nesting, shipbuilding, packing, cutting-stock.

### 1. Introduction

The task of finding an efficient layout for cutting 2D parts out of a given 2D sheet with minimum waste material is called "nesting". The number of applications, e.g. shipbuilding, textile and furniture industry, is very large.

Many numerical approaches are available in literature, which involve different strategies and solution techniques as genetic or swarm intelligence algorithm [1-3]. Several authors evaluate the no fit polygon techniques (NPF) [2, 4-5] which is based on the aggregation of 2 polygons and can be used to determinate the overlaps. This approach needs to convert the boundary of the surfaces into polygons. Another approach is based on the subdivision of the sheet in pixels [2, 6] adopting different coding schemes to denote the empty space. Other

methods are based on the sliding of the shells in the sheet as the bottom left (BL) [1, 7-8] or bottom-left-fill (BLF) [1, 9] approaches.

In actual industrial applications, several techniques (e.g. NPF) are not suitable and simpler methods, as the BLF approach, are preferred.

In the product development of a ship it is necessary to split the geometric model of the hull into shells. The shells must be unrolled in 2D surfaces having dimensions less than the sheet dimensions (e. g. 6000x2000 mm). Then, the shells are nested in metal sheets for the cutting process. Finally the shells should be bended and welded.

In this paper a part of a project for the shipbuilding industry, developed in IronPython - Rhinoceros® V.5 software (from McNeel), is described. More in detail, a plug-in for the naval carpentry management has been developed, which include:

- definition of the properties of the shells,
- creation of shells database
- tracking the welding lines and the reference frames,
- unrolling shells,
- nesting shells, described in this work.

The proposed nesting method is based on the identification of a preliminary optimal orientation of each shell, which is defined by the minimum area of the bounding box. This approach can be easily integrated with the traditional nesting algorithms: bottom-left [1, 7], minimum total potential or lowest-gravity-center and raster [2, 6-7, 9].

The results show a reduction of the waste material, with a minimum rise in computational time. Also using the Rhinoceros® built-in functions, the no-overlap condition is simple to check, the reduction of the surface to a polygon and the implementation of the NPF algorithm is not required, the welding lines and the reference frames can be moved together with the shell, and the respect of the distance between the shells can be obtained by offsetting the boundary.

## 2. Proposed nesting approach

As previously mentioned, the geometrical model of the hull is split into shells which are developed in 2D surfaces; each of them is saved in a separate model file.

Then, the nesting phase, summarized in Fig. 1, can take place. The first step is the importation and the preliminary rotation of several model files (i.e. shells) in the nesting model file. Afterward, a list of the shells is created and sorted according to the height of the bounding-box from largest to smallest. In order to allow the cutting process, the shells must be spaced (typical distance is 20 mm); this result can be obtained nesting the offset curve of the boundary of each shell, moving together the shell and its offset and then erasing the offset. Following a nesting procedure, selected among four options, the shells are placed in the sheet starting from the top right position and moving left and down until no-overlap occurs. Details are described in the following sections.

### 2.2. Preliminary orientation

Three orientations of the shell are investigated:

- the original orientation, i.e. the same orientation of the shell reference frame,
- the orientation based on the alignment of the maximum edge length with the x-axis,
- the orientation of the principal axes of inertia about the centroid with the sheet reference frame.

If necessary the shell is rotated of  $90^\circ$  in order to align the maximum edge of the bounding box together to the x-axis. The orientation which assures the minimum bounding box area of the shell is selected for the nesting procedure.

Figure 2 shows the application of the procedure to a shell having an hole and irregular boundaries. The original bounding box area is  $3.79 \text{ m}^2$ , the bounding box area with maximum edge is  $3.38 \text{ m}^2$  and the bounding box area with the principal axes of inertia aligned together to the reference frame is  $2.61 \text{ m}^2$ : the last one is assumed as the optimal orientation for the nesting.

### 2.3. Nesting rule

Four standard nesting approaches are tested in order to evaluate the improvement due to the preliminary orientation and to the sorting.

#### 2.3.1. BL Algorithm

One of the most widely adopted methods for nesting (especially in industry) is the bottom-left BL algorithm [1, 7-8]. Starting from the top-right corner of the sheet each item is slid to the left and then down until the item is close to another nested part or to the sheet contour. Adopting the pre-orientation and the sorting of the items the major disadvantage of the method (creation of empty

areas, when larger items block the following ones) is reduced.

Similar to literature the sliding method can be described by the following pseudo code, first applied to left and then to down directions:

```
for each shell:
  s=(base bounding-box)/2, t=0.1 mm
  offset shell
  move shell and offset-shell to top-right of sheet
  if no-overlap occurred:
    while s<t:
      slide to left (or down) shell and offset-shell by the step s
      if overlap:
        slide to right (or up) shell and offset-shell by the step s
      s=s/2
```

The overlap condition is checked by the Rhinoceros V.5 built-in function `PlanarClosedCurveContainment` between the boundary of the sheet, of the previously nested shells and of the actual offset-shell.

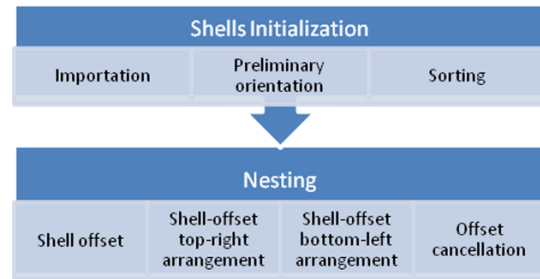


Fig. 1. Flow chart of the nesting procedure.

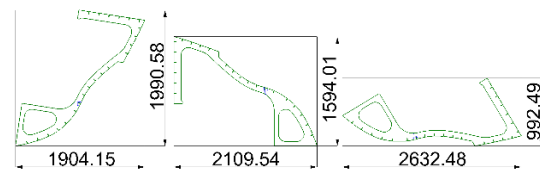


Fig. 2. Different preliminary rotation: original (left), maximum edge length (middle), principal axes of inertia (right).

#### 2.3.2. BL & HAPE integrated algorithm

Minimum total potential energy (HAPE) or lowest-gravity-center principles are based on the minimization of the distance between an edge of the sheet and the centroid of the shell.

This approach can be implemented testing different rotations and applying the BL algorithm. Considering the preliminary orientation of the parts, a rotation at  $90^\circ$  steps may be sufficient.

The free part covering the full height of the sheet (free length) is not considered in the evaluation of the wastage. Consequently, in the last sheets, this approach can be useful if there are shells of elongated shape: vertically aligning these shells, the free length increases and the wastage decreases.

### 2.3.3. BL & Raster integrated algorithm

Raster methods are based on the subdivision of the sheet in points or pixel [2, 6-7, 9]. The simplest coding scheme uses the value 1 to code the area of the sheet covered by a shell, and 0 to code the free area.

In this work a variation of this method is applied to improve the nesting of shells with holes. Initially the shells are nested as in the BL method. When the area of the bounding box is greater than 80% of the shell area, the bounding box of the nested shell is covered by a grid of points with a constant step along the x and y-axis. If the points fall offside the shell, they are put in a list. The shells having smaller area are tested. Each shell is set on each point in the list until no-overlap happens. When this condition occurs the BL procedure is applied and the points inside the shell are deleted from the list.

The left-bottom vertexes of the shells with smaller area are put in the first point of the list. For each shell if no-overlap occurred, the BL procedure is applied and the points inside the shell are removed from the list.

### 2.3.4. BL, HAPE & Raster combined algorithm

This approach is obtained combining the methods descibede in the paragraphs 1.2.3.2-1.2.3.3.

in relation to the preliminary orientation. The "BL & Raster" method performs all shells in a short time. The high value of wastage material in the last sheet is due to the high number of shell with small area and to the minimum distance between the shells. The best result is obtained with the combined method; in this case more than 4 meters of the last sheet remains unused (free length).

Figure 3 shows the results of the nesting on the first sheet. As it is possible to see, sometime the combined used of the raster and HAPE approach don't give any improvement (in sheet 1 the best results is given by the BL & raster approach, while in sheet 2 and 3 the best results are given by the BL and HAPE method). Effectively in the first nesting step the HAPE method can create empty areas when larger items block the successive ones, while in the final step the HAPE method can be useful to get better free length in the last sheet. Thus it can be useful to start with the raster approach and to follow with the HAPE. Figure 4 shows the result of a nesting with BL & Raster in the first sheet and BL & HAPE for the second sheet. In this way the total time for the nesting procedure is about 2 minutes and the total waste material decrease to 23 %, with a free length of 4459 mm.

## 3. Results and discussion

The proposed approaches have been tested on the nesting of 152 shells with and without the preliminary rotation.

The shells initialization task has been performed in 6 s, 5 of which were used to import the file.

The results summarized in Table 1 have been obtained assuming:

- sheets dimension 6000x2000 mm,
- shell-shell minimum distance 20 mm,
- rotation step 90° for the HAPE approach,
- points step 100 mm for the raster approach.

For the nesting of all the shells, three sheets are needed. The BL approach is the faster, while the combined is slower. It can be seen that the wastage material is smaller adopting the preliminary orientation, while the time necessary to perform the nesting has no clear behaviour

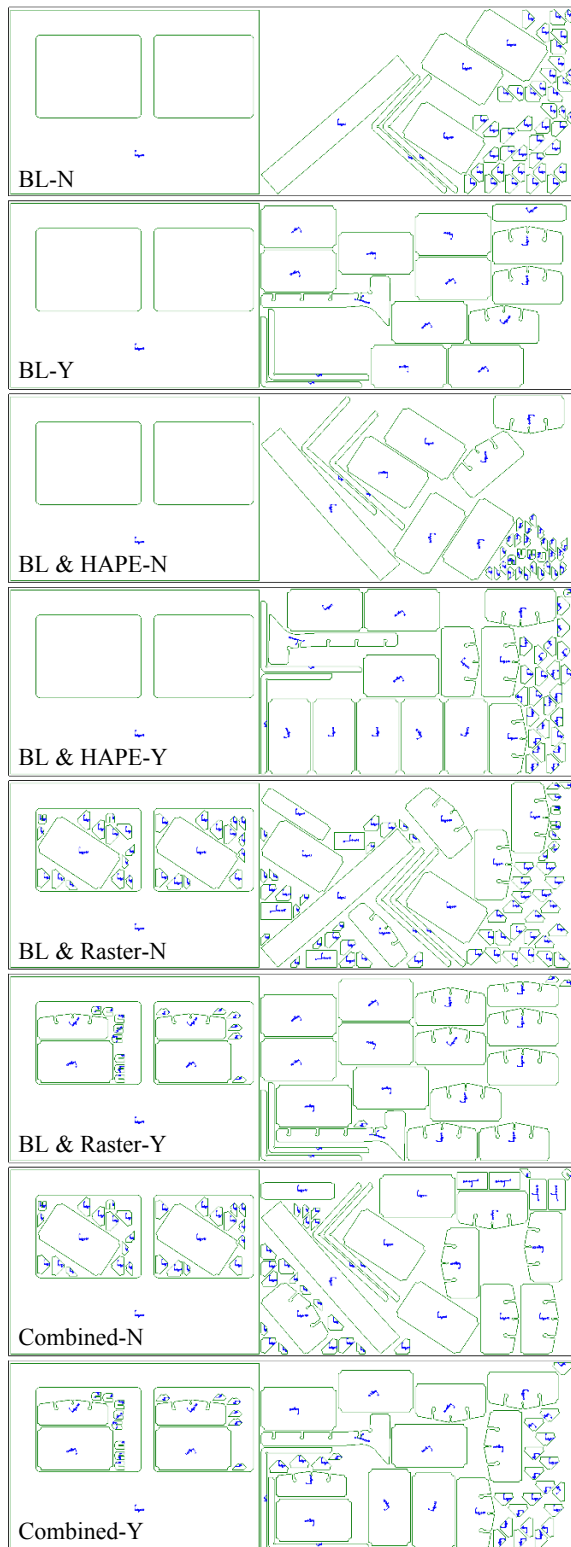
## 4. Conclusion

In this paper a modification of the standards nesting procedures is proposed introducing a preliminary orientation of the parts based on the minimization of the bounding box area and on the sorting by the height of the bounding box. The results show that the approach reduces the time necessary for the nesting and decreases the waste material.

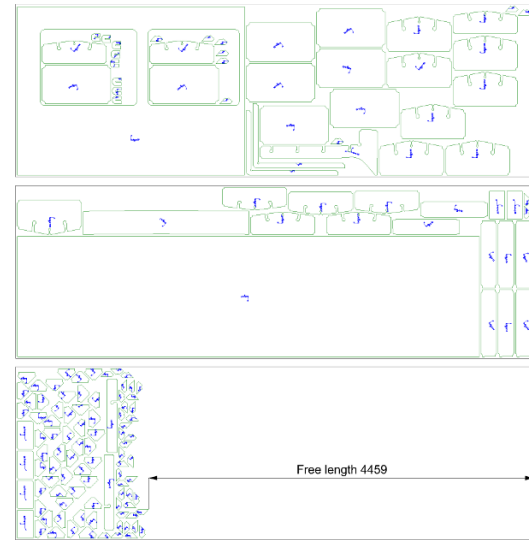
**Table 1.** Nesting of 152 shells: calculation time, waste material\*\* and free lenght in the last sheet performed with (Y) or without (N) preliminary orientation.

Algorithm	Time [s]				Wastage [%]								Free lenght last sheet [mm]	
	1 sheet		All shells		Sheet 1		Sheet 2		Sheet 3		Total			
	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y
BL	6.4	2.8	26.2	45.7	52.7	38.3	35.3	19.5	47.1	47.1	47.5*	33.1	4147*	2416
BL & HAPE	14.5	19.4	141.4	155.7	49.6	33.7	17.4	16.5	43.6	40.7	36.1	27.7	1672	3570
BL & Raster	71.0	23.5	137.3	44.3	36.2	25.4	30.0	18.8	48.0	54.7	37.3	27.5	1382	3616
Combined	85.6	54.1	159.2	170.4	31.5	28.7	20.8	16.5	54.6	41.3	32.4	25.2	2565	4057

\* Four sheets are needed. \*\*  $100 \cdot (\text{Sheet\_area} - \text{Area\_of\_nested\_shells}) / \text{Sheet\_area}$



**Fig. 3.** Comparison of different nesting approach with (Y) or without (N) preliminary orientation. From top to down: BL-N, BL-Y, BL & HAPE-N, BL & HAPE-Y, BL & Raster-N, BL & Raster-Y, Combined-N, Combined-Y.



**Fig. 4.** Mixed Approach: the first sheet is nested with the BL & Raster, while the second and the third sheets are nested with the BL & HAPE method.

**Acknowledgments:** The authors are grateful to 3jyachting srl for the financial support.

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## STEP-NC compliant manufacturing cost estimation system for CNC milled part component

Abayomi B. O. Deboade, Aydin Nassehi, Linda B. Newnes and Stephen T. Newman  
Department of Mechanical Engineering, University of Bath, Bath, BA2 7AY

**Abstract.** Manufacturers depend on cost estimation system, at the early stage of product development, to support engineers' decision on design alternatives toward reducing final product cost. Lack of detail information about a product and its manufacture to generate fast and accurate cost estimate is a critical challenge in integrated manufacturing environment today. Most cost estimation systems rely on expert opinion and nominal information about the product to generate cost estimate of questionable accuracy. High level integration of cost estimation system with manufacturer's other computer aided systems for seamless exchange of actual design and process information about a product can potentially improve the accuracy of cost estimate. However, each computer aided system, including current integrated cost estimation systems, uses vendor-specific programming for unidirectional communication with other manufacturer's systems. This hinders seamless flow of actual information about the product that is required for fast and accurate cost estimation during product development. Implementation of a vendor-neutral communication language will facilitate bidirectional sharing of quality information for interoperability and accurate cost estimate. In this paper the evolving ISO 14649 standard (STEP-NC) is implemented as a vendor-neutral medium for high level integration of estimation system with other computer aided systems for fast and accurate cost estimation.

**Keywords:** Cost estimation, Integrated manufacturing, STEP-NC

### 1. Introduction

In recent years cost estimation systems have been developed and used by manufacturers to support cost reduction decision during product development.

Existing cost estimation systems used in providing cost related information to design engineer for design alternatives assessment in a traditional product development were reported to have suffered from little or no integration capability with manufacturer's computer aided systems (CAx). They rely on manual data input and depend on expert opinion as well as, historical database. The estimation process also involves time consuming and costly data gathering and analysis [1].

In the past decades, computer aided systems (CAx), such as CAD, CAM, CAPP and CNC are widely used in

manufacturing industries and international efforts have led to the development of Standard for the Exchange of Product data model (STEP) that enable total integration of CAx. The use of STEP for the exchange of design data is gaining momentum in manufacturing industry. In the same way, ISO 14649 also referred to as, STEP compliant Numerical Control (STEP-NC), is evolving as a viable solution to bi-directional exchange of information in integrated manufacturing environment [2].

Product design, process and resource models are represented in a STEP-NC data file. This provides an opportunity for the development of high level integrated cost estimation system that utilises these actual product information to generate improved cost estimate. This paper presents a methodology that utilises part design and process information available in STEP-NC file, to generate product cost estimate for a prismatic part. The STEP-NC compliant methodology facilitates high level integration with other CAx for improved accuracy of cost estimate and reduces expensive and time consuming data gathering and analysis activities for cost estimation.

### 2. Manufacturing cost estimation

There are a number of cost estimation techniques that have been reported in literature, Parametric, Analytical and Analogical methods are widely used in manufacturing industry [3]. These methods were applicable to early stages of product development where there is lack of detailed information about a product. Integration of cost estimation system for gathering of available data to support product costing can improve accuracy of estimate.

Various methodologies for integrated cost estimation have been reported in the literature [4]. Reviewed integrated cost estimation methodologies applied a set of rules to generate process plan from a feature based CAD model, calculate the expected material volume removed and use the integrated value to generate product cost



estimate. Being rule based, reported integrated cost estimation lack capability to adapt to manufacturing process innovation. Also, they require extensive manual data input and are therefore susceptible to human induced errors. Furthermore, they do not take into account, secondary finishing process that may be required to achieve a specified surface finish, to improve cost estimate accuracy.

Accuracy of cost estimates improves with the quality of data used to generate it. In an integrated manufacturing environment cost relevant data are available as output at the multiple computer aided systems such as CAD, CAPP, CAM, and CNC that were used to perform product development activities. Utilization of these available data to generate cost estimate require high level of costing system integration with other integrated systems but the replacement of the current uni-directional communication language with a unified bi-directional communication medium for information exchange between manufacturing systems is a critical challenge that require solution. STEP-NC provides an opportunity for the development of a compliant cost estimation system that can utilise CAX outputted data to generate product cost estimate.

### 3. Product development and STEP-NC

A STEP-NC compliant adaptive manufacturing platform has been developed by the AMPS team at the University of Bath's Mechanical Engineering Department [5]. The high level integration of the component part of the platform is illustrated in Fig. 1. Based on this platform a STEP-NC compliant estimation system for manufacture (SCES-M) is proposed.

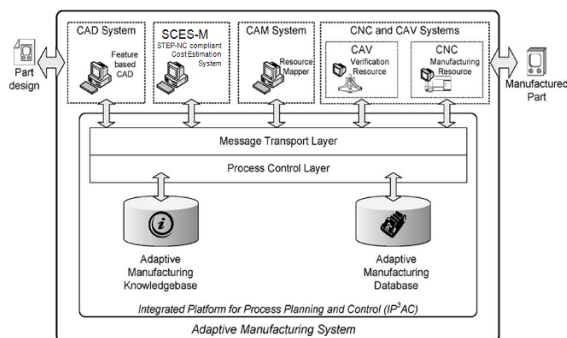


Fig. 1. STEP-NC compliant integrated platform (adapted from [5])

The proposed SCES-M benefits as a component part of the STEP-NC compliant integrated platform. The platform associates the data exchanged with each component with the semantics of the information handled by that component. As a result, the CAD, SCES-M (costing), CAM, and CNC, utilise for product development communicate through specific interfaces in

the platform instead of having to translate and transfer information individually. These interfaces are STEP-NC compliant for bi-directional information exchange. The CAD interface for example interprets the information received from a CAD package and associates the highest level of semantics that are available for that specific system with the received data, such as geometric features, tolerance and surface finish. These are then passed to the CAM interface where domain specific knowledge is utilized to transform the information to a suitable format for a specific CAM package. The CAM package manipulates the information and sends additional data in the form of manufacturing information to the CAM interface. The interface parses the information and creates the necessary links to maintain the semantic validity of the product model. Complete manufacturing information is then passed on to the CNC interface where the knowledge driven system utilizes the available data to create a suitable set of instructions for part machining. As semantics are retained in the platform, every single piece of information is captured and linked to the rest of the available data in a synchronized manner. This maintains information integrity at all times and ensures that the quality information is made available at all stages of product development.

The result is that SCES-M that is plugged-in to the platform can access and utilise actual design and process information to quickly generate part cost estimate with improved accuracy. This STEP-NC compliant methodology ensures that cost based support for decision on the alternative, during product development, is not confined to the early stage but extends right down to the manufacturing stage.

### 4. The proposed system

The functionality of SCES-M systems can be described using a flow diagram shown in Fig. 2.

The process of estimating the cost of a machined part begins with a STEP-NC data file input. STEP-NC file contains design, processes and resources models representation that provide semantically structured cost relevant parameters for machining time and cost estimation. Based on the high level integrated structure discussed above, the SCES-M process for estimating the cost of a machined part is illustrated in Fig. 2 below. The process can be summaries as follows:

**1st** – The system read STEP-NC files and extract the machining feature and process parameters from the data file.

**2nd** – The manufacturer database is interrogated for available resources and a machine tool specific process plan is generated based on expected finished features. The process plan parameters are then extracted for use at the next stage of the estimation process.

**3rd** – An algorithm utilises the extracted machining parameters to generate machining time estimate for each

operations performed to realized a finished part. The following expression is used to calculate the machining time for each operation:

$$t_i = \sum_{j=1}^n t_j \quad (1)$$

Where  $t_i$  is the machining time for each feature (min) and  $t_j$  is the machining time for each operation (min).

4th – The sum of estimated time for the machined features are then caculated to obtain the overall machining time estimate. The following expression is used:

$$t_p = \sum_{i=1}^m t_i \quad (2)$$

Where:  $t_p$  is machining time estimate for part (min) and  $t_i$  is the machining time for each feature (min).

5th – The system interrogates the manufacturer accounting database for relevant shop and labor rates which are use for machining cost calculation. The machining cost is calculated using expression below:

$$C_m = t_p \times (C_h + L_r) \quad (3)$$

where,  $C_m$  is the part machining cost (£);  $t_p$  is the estimated machining time (min);  $C_h$  is the hourly cost of a machine and;  $L_r$

$$C_m = (0.045) * (45+14) = £2.67$$

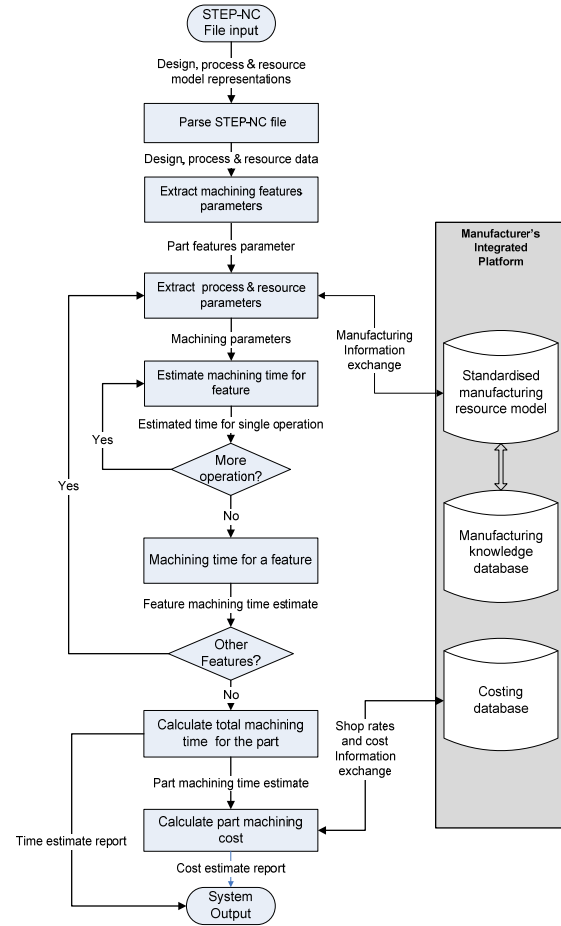


Fig. 2. SCES-M process flow diagram

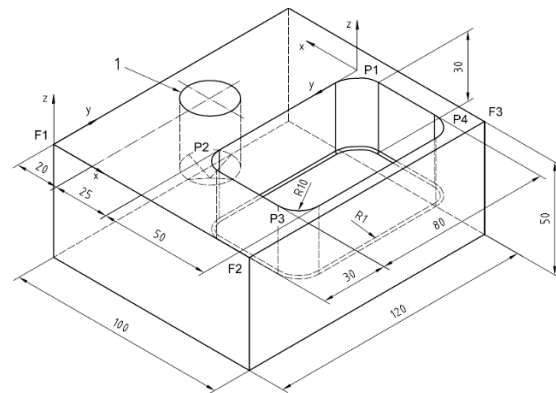


Fig. 3. Milling test component [2]

Based on reported machining time estimate for the example milled part and generic manufacturer's shop rate the above cost per hour has been calculated for the part

using STEP-NC file as the information source for the cost estimate. High percentage of medium to high volume manufacturers based their cost estimate on combination of machine hour and production time [7] and the implementation of STEP-NC for high level integrated cost estimation provide the basis for fast cost estimation.

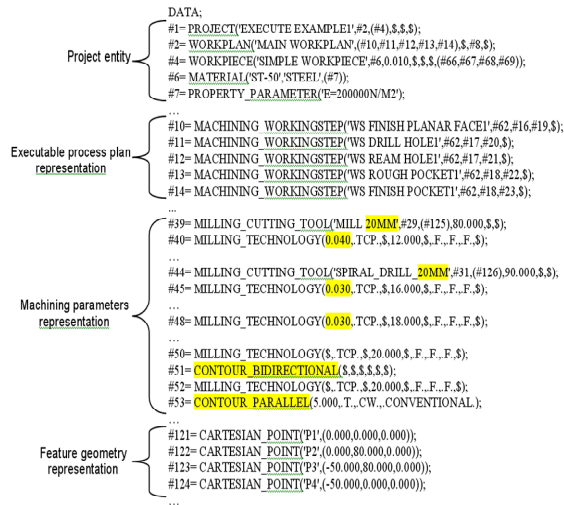


Fig. 4. STEP-NC design and process information category for the example test part [2]

## 6. Conclusion

With the changes in manufacturing technologies a systemic approach to integrate concurrent design of product and their related processes, for shorter product development cycle, better quality, and reduction of manufacturing cost, have become industry standard. Cost estimation systems are used by manufacturers for timely decision support on reducing manufacturing cost. It is then useful and beneficial approach to reduce the time taken to generate accurate estimate. This paper has presented a STEP-NC compliant estimation system with high level integration capability for machined part cost estimation. The presented estimation system obtains detailed cost parameters from a STEP-NC file and implements algorithm to generate machining cost estimate. This paper demonstrates the feasibility of the ISO standard [2] to facilitate high level integrated cost estimation in a manufacturing environment. This paper demonstrates the benefit to be had from such an approach. Furthermore, the presented methodology provides manufacturer with actual product and processes information to generate fast and accurate cost estimate. Further work will focus on demonstrating the potential application of such system to support decision on alternatives at all stages of product development and extending this STEP-NC compliant methodology to support decision on optimum manufacturing resources

selection by generating and comparing production cost estimate (for a given part) for a number of machine tools (CNC). The result will be used to support decision on optimum manufacturing resource alternative.

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## Automated design and STEP-NC machining of impellers

Arivazhagan Anbalagan<sup>1</sup>, Mehta NK<sup>2</sup> and Jain PK<sup>2</sup>

<sup>1</sup> Indian Institute of Information Technology Design & Manufacturing, Kancheepuram, Chennai – 600 048, INDIA.

<sup>2</sup> Indian Institute of Technology Roorkee, Roorkee – 247 667, INDIA.

**Abstract.** This paper presents the four stage approach followed for automated design and STEP-NC based machining of impellers. In the first stage, the design calculations are performed to construct the 'Meridional representation' of the radial impeller. Then 3D curves are projected from the 'Meridional representation' and 3D model is generated using UG-NX software. In the second stage, the process planning activities including tooling & setup plan are completed. Here, ball end mill cutters with suitable diameter and length are selected and appropriate process parameters as suited to 5 axis milling are considered. In the third stage, the tool path data based on contour area milling is generated and verified in the UG NX software. Finally, in the fourth stage, the model with the complete data is imported to STEP-NC software and the AP-238 format is generated. In this article the design procedure adopted for construction of 'Meridional Section' of a radial turbine is discussed with the general methodology to automate the process planning and tool path generation. A test case of radial impeller is presented with the results obtained by adopting STEP-NC format.

**Keywords:** Impellers / Blades, Modelling & Automation, CAPP, STEP-NC Integration

### 1. Introduction

Automated design & STEP-NC machining of impellers is considered to be a crucial task as it involves integration of complex design procedures and 5 axis manufacturing process plan data. Impellers which are free form in nature are adopted to pump the flow of gas or fluid in centrifugal & axial compressors/turbines/pumps belonging to oil and gas (O&G), aviation and power generation domains. Generally, these are first casted and then finish machined using a 5 axis milling machine and sometimes completely milled in a 5 axis milling machine. In either case, a manufacturing drawing sheet must be generated from a parametrically strong and geometrically precise 3D CAD models. These 3D CAD models are designed by sweeping the basic curves namely (i) B-Spline and (ii) NURBS which follows recursive blending mathematical representations. The construction procedure of these curves and surfaces are well known [1] and implemented in many CAD/CAM packages. From an automated manufacturing point of view, these 3D CAD models

should contain error free feature data, as even a minor change leads to improper process plan and tool paths. Further, process plan independent CL data generated from these models consumes more time for post processing in a CNC machine. In the present scenario, CL data alone is not sufficient to go ahead with the machining process. Addition details such as tooling, setup and fixture is required to proceed with a robust machining. As regards, researchers adopt STEP/STEP-NC technology owing to the advantage of integrating product life cycle and manufacturing process planning data. Also, it reproduces error free 3D CAD models and reduces the transfer time to a major extent. Even though there are many advances in this domain, automated design and STEP-NC machining of impellers needs attention owing to the complexity encountered while automatic feature recognition, design calculations and generation of process plan with tool paths. HT Young et al. [2] generated tool paths for rough machining centrifugal impeller using a five axis milling machine. They introduced two concepts namely (i) residual tool path and (ii) cutting tool path for removing the material which are closer and away from the blade tip. Pyo Lim [3] presented an approach to optimize the rough cutting factors of impeller with a 5 axis machining using 'response surface methodology'. In his work, the roughing operation is divided into five portions to machine the fillets between blade surfaces and hub surfaces. Julien Chaves-Jacob et al. [4] presented an optimal strategy for finish machining the impeller blades by adopting a 5 axis milling machine. Here, point milling and flank milling strategies are developed to reduce the machining time. Li-Chang Chuang & Hong-Tsu Young [5] presented an integrated rough methodology to manufacture centrifugal impeller. While rough machining constant scallop height is maintained to improve the quality of machining process. They analyzed a theoretical model and developed process plan for machining the part in a 5 axis milling machine. Toh [6] developed a strategy for cutter path calculation in high-speed milling process. He focused on rough machining of moulds and tested the tool



paths using a vertical high-speed-machining centre. An algorithm for parametric tool path correction in a 5 axis machining has been proposed by Gabor et al. [7]. In their approach, machine dependent and independent data is developed to store the prescribed tool path. A machining strategy for milling a set of surface which is obtained by the technique of cross sectional design is performed by Sotiris & Andreas [8]. The surfaces are formed by sliding the Bezier Curve (Profile curve) along another Bezier Curve (Trajectory) and tool-paths are generated by offsetting the boundaries of the profile curve matching with the trajectory curve. He used data point models and produced LOD models and obtained adaptive rough-cut and finish cut tool-paths. Brecher et al. [9] tested STEP-NC program and inspected the feed back in a closed loop CAPP/CAM/CNC process. In their work, they modelled the component in a CAD package and generated the process planning details and validated in a STEP-NC based milling machine. A frame work to interpret the data in AP-238 is done by Liu et al. [10]. In their work, a PC based STEP-NC prototype for STEP compliant CNC is developed to interface and to extract the details required for processing the AP-238 format. After analyzing the literatures, the following points are noticed:

- Machining is conducted without addressing the design calculation of impellers
- 5- axis milling ignores the integration of process planning and tool path data in a single format
- There is still a complexity on roughing out the excess material in between the blades.
- While machining, there is a necessity for most efficient tool path, where the tool spends only a minimum amount of time in air.
- The tool length needs to be kept to the minimum to avoid vibration and to prolong tool life
- Focus must be given for integration of tooling, setup and fixturing aspects
- STEP-NC integration focuses on simple rotational, prismatic and sheet metal parts and not for impellers

Based on the above points, it is decided to proceed with an automated design and STEP-NC machining of impellers. As the first step, the design procedures adopted in impellers are analysed. It is noticed there are more than 20 design parameters involved in impeller design process. The next section presents the design calculation and its automation carried out in this research.

## 2. Design calculation of impellers

The design of an impeller is considered to be most complicated and crucial as there are more than 20 design parameters. These parameters are related to various flow parameters of compressor/pumps and is to be checked in accordance with the desired output. Fig.1(a) shows an impeller with few basic parameters namely (i) a leading edge-as pointed at its top (ii) trailing edge-as pointed at its end; (iii) hub diameter

- (iv) hub height (v) shroud (vi) hub & shroud surface and (vii) blade thickness.

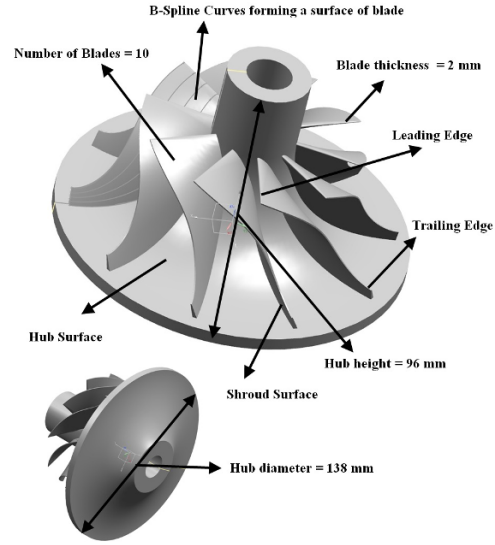


Fig.1(a). Radial Impeller cross section

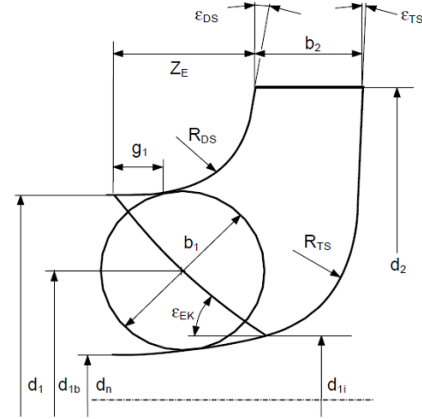


Fig.1(b). Meridional view of radial impeller

In order to draw a 3D impeller it is indeed necessary first to draw the section through the impeller called 'Meridional Representation'. Basically, the leading and trailing edges of a blade are projected into the drawing plane through 'circular projection' and the initial blade profile is drawn [12]. A 'Meridional representation' with various basic parameters required for construction is shown in Fig. 1(b). It consists of parameters namely (i)  $b_1$ -impeller inlet width (leading edge) =  $\frac{1}{2} (d_1 - d_n)$ ; (ii)  $b_2$ -impeller outlet width (trailing edge); (iii)  $d_1$ -Impeller inlet diameter; (iv)  $d_2$ -Impeller outer diameter; (v)  $d_{1i}$ - Blade inlet diameter at the inner streamline; (vi)  $d_{1b}$ -stream line diameter; (vii)  $R_{DS}$ -Radius of curvature - front shroud =  $(0.6 \text{ to } 0.8) b_1$ ; (viii)  $R_{TS}$ -Radius of curvature - rear shroud or hub; (ix)  $Z_E$ -Axial Extension; (x)  $\epsilon_{DS}$ - angle of front shroud; (xi)  $\epsilon_{TS}$ -angle of rear shroud or hub; (xii)  $\epsilon_{EK}$ -axial inlet angle; (xiii)  $d_n$  - Hub diameter; (xiv)  $g_1$ -



Short section length = (0.2 to 0.3)  $b_1$ ; (xv) e-Blade thickness; (xvi)  $d_w$ - Shaft diameter; (xvii)  $z_{La}$ - Impeller blade number; (xviii)  $\beta_{1B}$ - Impeller blade inlet angle; (xix)  $\beta_{2B}$  - Impeller blade Outlet angle and ; (xx)  $A_{1q}$ -Throat area.

Further to the above design formulas the following points are also considered: (i) In order to achieve a flatter pressure, the radius  $R_{DS}$  should not be tangent to the point defined by  $z_E$ , but a short section  $g_1 = (0.2 \text{ to } 0.3) \times b_1$  should be introduced with only a minor increase in radius (ii) For short axial extension of the impeller, smaller values are selected for  $z_E$  and  $R_{DS}$  than calculated from Eq. (1) (iii) Specific speed is used to find the angle  $\epsilon_{DS}$  (iv)  $\epsilon_{DS}$  is increased to 15 to 20° with higher specific speeds (v) Positive or negative angle for  $\epsilon_{TS}$  can be chosen and (vi) The outer streamline is drawn with  $d_2$ ,  $b_2$ ,  $d_1$ ,  $z_E$ ,  $g_1$ ,  $\epsilon_{DS}$  and  $R_{DS}$  defined by a free curve or assembled from straight lines and circular arcs or by Bezier functions. To proceed with the calculation of the basic parameters namely,  $d_1$ ,  $d_2$ ,  $d_{1opt}$ ,  $z_E$  etc. the Equations from Eq.1 to Eq.6 are adopted.

$$d_1 = 2.9 \sqrt[3]{\frac{Q_{La}}{f_q n k_n \tan \beta_1} \left(1 + \frac{\tan \beta_1}{\tan \alpha_1}\right)} \quad \text{Eq. (1)}$$

$$d_2 = \frac{60}{\pi n} \sqrt{\frac{2g H_{opt}}{\psi_{opt}}} = \frac{84.6}{n} \sqrt{\frac{H_{opt}}{\psi_{opt}}} \quad \text{Eq. (2)}$$

$$d_w = \left(\frac{16P_{max}}{\pi \omega \tau_{a1}}\right)^{\frac{1}{3}} = 3.65 \left(\frac{P_{max}}{n \tau_{a1}}\right)^{\frac{1}{3}} \quad \left| \begin{array}{l} P_{max} \text{ in W} \\ n \text{ in rpm} \\ \tau_{a1} \text{ in N/m}^2 \end{array} \right. \quad \text{Eq. (3)}$$

$$z_E = (d_{2a} - d_1) \left(\frac{n_q}{n_{q,Ref}}\right)^{1.07} \quad \left| \begin{array}{l} R_{DS} = (0.6 \text{ to } 0.8) b_1 \\ b_1 = \frac{1}{2} (d_1 - d_n) \\ n_{q,Ref} = 7.4 \end{array} \right. \quad \text{Eq. (4)}$$

$$d_{1,opt} = \sqrt{d_n^2 + 10.6 \left(\frac{Q_{La}}{f_q n}\right)^{\frac{2}{3}} \left(\frac{\lambda_c + \lambda_w}{\lambda_w}\right)^{\frac{1}{3}}} \quad \text{Eq. (5)}$$

$$\beta_{1B} = \beta'_1 + i_1 = \arctan \frac{c_{1m} \tau_1}{u_1 - c_{1u}} + i_1 \quad \text{Eq. (6)}$$

To find the various parameters initially, the values of the first 7 parameters are assumed. The remaining are calculated accordingly with their specific formulas. Further, due to page restriction, partial calculation is shown with the basic parameters assumed for few dimensional parameters. The author can be emailed for the complete calculation part of the impeller. (i)  $d_n = 1.36$  m; (ii)  $\alpha_1 = 60^\circ$ ; (iii)  $\alpha_2 = 35^\circ$ ; (iv)  $\beta_1 = 30^\circ$ ; (v)  $\beta_2 = 37^\circ$ ; (vi)  $\beta'_1 = 45^\circ$ ; (vii)  $\beta'_2 = 52^\circ$ ;  $i_1 = 15^\circ$ ;  $i_2 = \delta' = 10^\circ$ ;  $\beta_{1B} = i_1 + \beta'_1 = 60^\circ$ ;  $\beta_{2B} = i_2 + \beta'_2 = 60^\circ$ ;  $\delta = \beta_{2B} - \beta_2 = 25^\circ$ ;  $H_{opt} = 10$  m;  $n = 3000$  rpm;  $\lambda_c = 1.2$  to  $1.35$ ;  $\lambda_w = 0.42$ ;  $C_{1m} = Q_{La} / f_q A_1$ ;  $A_1 = (\pi/4) (d_1 - d_n)^2$ ;  $C_{1u} = C_{1m} / \tan \alpha_1$ ;  $Q_{La} = Q_{opt} + Q_{sp} + Q_E$ ;  $Q_{opt} = 8.9$  m<sup>3</sup>/s;  $Q_{sp} = 1.9$  m<sup>3</sup>/s;  $Q_E = 0$ ;  $K_n = 0.2$ ; The calculated values are given below:

$Q_{La} = Q_{opt} + Q_{sp} + Q_E = 10.8$  m<sup>3</sup>/s;  $d_1$  – based on Eq.1 = 0.241m;  $d_{1,opt}$  – based on Eq.1 = 1.30m;  $d_1$  – based on Eq.2 = 0.0893m;  $z_E$  – based on Eq.4 = 0.684;  $R_{DS}$  – based

on Eq.4 = 0.84m ; After making all the basic calculations the “Meridional Section” is drawn using UG NX software. The 3D representation is also drawn in the UG-NX software from the ‘Meridional section’ by adopting a similar set of calculation.

### 3. General methodology adopted in automation process

**Step1:** Design the radial impeller and model the part in UG NX CAD package

**Explanation to Step1:** In this step, the part is modelled and parameterized in the UG NX CAD package. Geometric dimensioning and tolerances (GD&T), information of datum's are added to the model. Then drawing sheets associated with the parts are manually generated and checked.

**Step2:** Using UG/UFUNC functions extract the geometrical and topological data of the model.

**Sub step2.1:** Ask the tag (number) of part (specific to UG)

**Sub step2.2:** Using the tag, cycle all the objects in the part and count the number of features/ objects.

**Sub step2.3:** Get the ID's of all features/objects

**Sub step2.4:** Extract the data and store it in a text file.

**Explanation to Step2/Sub steps 2.1-2.4:** Generally, a UG part model will have a single tag in the form of a number. This is extracted and the tags of various sub features / objects are found by cycling the part model through a UG/UFUNC function “UF\_OBJ\_cycle\_objs\_in\_part”. Using these tags the geometry and topological data of the sub features / objects are extracted which is used to find the closeness index with Bezier /B-Spline curves. Some of the other used functions are: (i) UF\_CURVE\_ask\_spline\_data (ii) UF\_CURVE\_edit\_spline\_feature(iii) F\_b\_curve\_bezier\_subtype.

**Step3:** Match the data with the basic B-Splines / Bezier curves / surfaces and calculate the closeness index

**Explanation to Step3:** In this step, the extracted data is matched and a closeness index (CI) “0(0-not matching)-10 (10-exact match)” is generated. It is done by calculating the control points, degree of meridional curve, and various parameters (as shown in Fig.1(b)) required for Bezier and uniform/ cubic/open/non-uniform B-Spline curves.

**Step4:** Calculate the blending functions and identify the machinable area of the impeller / blade features.

**Explanation to Step4:** After finding the closeness index blending functions are calculated using convolution theorem. Using the blending function data, the rough and finish cut machinable volumes are calculated.

**Step5:** Specify the process plan details and Adopt the Z-level contour area milling to generate tool paths

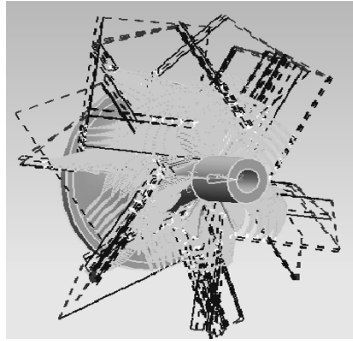
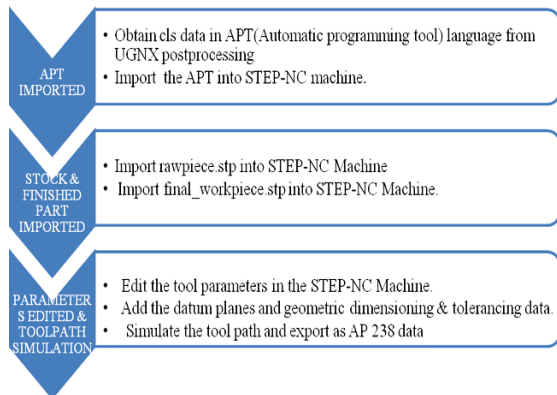
**Explanation to Step5:** Here, ball end mill cutters with appropriate radius and length are used for machining.

**Table 1.** Process Plan details of the radial impeller

Roughing	Finishing
Ball End mill	Ball End mill
Diameter = 8 mm	Diameter = 5 mm
Length=75 mm	Length=75 mm
Flute length= 50 mm	Flute length= 50 mm
Feed rate	23 mm/min
Spindle speed	2500 rpm

Appropriate process parameters for 5 axis contour area milling as shown in Table1 is adopted for machining.

The work piece is rotated to make cutting surfaces of tool tangent to ideal part features. Two methods namely (i) fixed and (ii) variable contour machining methods are used to finish areas formed by free form surfaces. Intricate contours are machined by controlling tool axis & projection vector. A schematic representation of the impeller machining process is shown in Fig. 2. The tool path is simulated for both roughing & finishing operations and CL data is obtained after post processing.

**Fig.2** Tool paths simulated with GD&T data**Fig.3.** Steps followed to obtain a AP-238 data.

**Step6:** Integrate and verify with STEP-NC format

**Explanation to Step6:** Finally, the impeller is machined using standard method of tool path generation available in STEP-NC Machine as shown in Fig.3. The tool path is finally simulated & output file is obtained as AP238 format.

#### 4. Conclusions and future work

The whole process is automated through a software named Free\_Form\_Blades\_Impeller\_Automation F<sup>2</sup>BIM). It consists of four modules namely (i) Design Module (DM) (ii) Process Planning Module (PPM) (iii) Tool Path Generation Module (TPGM) and (iv) STEP-NC generation Module (STM). All these modules are linked with the main GUI of the software. A user can select/modify various blades / impellers as suited for industrial needs and can generate the complete set of data required for machining. Presently, cross sectional details of 3 radial impellers are automated. Work is in progress to upgrade the whole software with more than 50 different types of profiles collected from various engineering domains.

**Acknowledgements:** The author gratefully acknowledge Department of Science and Technology (DST), Government of India for funding this research under SERC-Fast Track Scheme for Young Scientists (FAST).

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## LACAM3D, CAM solution for tool path generation for build up of complex aerospace components by laser powder deposition

J. Flemmer<sup>1</sup>, N. Pirch<sup>2</sup>, J. Witzel<sup>1</sup>, A. Gasser<sup>2</sup>, K. Wissenbach<sup>2</sup>, I. Kelbassa<sup>1,2</sup>

<sup>1</sup> Chair for Laser Technology, RWTH Aachen University, Germany

<sup>2</sup> Fraunhofer Institute for Laser Technology ILT, Steinbachstr. 15, Aachen, Germany

**Abstract.** This The success of Laser Metal Deposition (LMD) for repair or fabrication of near-net shaped metals components directly from CAD solid models without use of time and cost-prohibitive conventional techniques, such as five-axis milling, linear friction welding and electro chemical machining depends on the availability of a close CAD/CAM chain. Distortion and defects of a worn part implies that the nominal CAD model from the design stage is no longer suitable for the representation of the part geometry. This means that first of all the actual and the target geometry have to be constructed from which the deficit volume is determined. Only with this volume being available the tool path programmed. The original data format of laser scanned data is a polygonal modeling approach for surface representation. The further step of creating a NURBS representation of the geometry requires a major commitment in time, both in instruction and in amount of work. For this reason the ILT designed a process chain for the LMD whose CAM module, LACAM3D, is based on a polygonal modeling approach for geometry representation. NURBS are only used for the reduction of data noise in the scanned data. The target geometry of worn parts is derived by a best fit with the CAD model from the design stage. LACAM3D supports the generation of all sorts of path pattern within a layer which for example may be derived from a distortion reduction analysis. The functionalities of LACAM are exemplified by a repair application and the near-net fabrication of a BLISK (Blade-Integrated diSK) blade direct from the CAD model.

**Keywords:** Laser powder deposition, reverse engineering, CAM

### 1. Introduction

LMD is under development in the last few years and just becoming an advanced manufacturing technology for repair or fabrication of near-net shaped metals components. LMD is an additive-layered technique that uses a laser beam to melt injected powder or wire along the tool path and thereby to form the layer by adjoining clad tracks. Due to various defects such as distortion, wear or manufacturing tolerance the most components don't correspond to the geometry data specified in the nominal CAD model. For this reason the actual and the target geometry have to be constructed in order to establish a sound CAD basis for tool path generation.

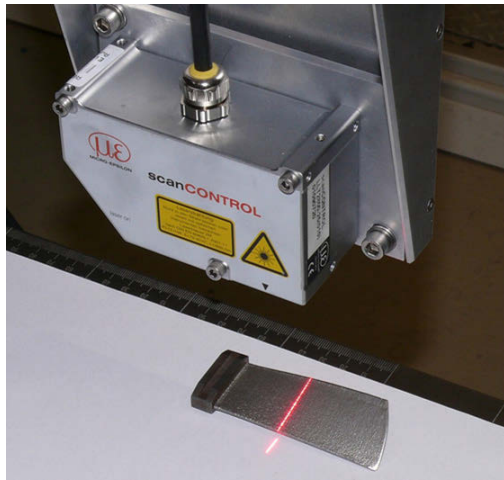
Almost all CAD programs have the ability to transfer geometry data based on NURBS modeling to polygon representation in a desired accuracy. Reverse engineering derives in the very first step a polygonal geometry representation from the point cloud of scanned data. So polygon modeling i.e. the so called stl format is supported by CAD and reverse engineering. Concerning the geometry construction from scanned data there is a need for research for shape preserving data noise reduction and automatic edge detection.

Because polygon modeling is the very first step in reverse engineering the ILT decided to use a geometric modeling kernel for the CAM module, LACAM3D, which uses exclusively the stl data format. Thereby the complex procedures for NURBS representation of scanned data can be avoided. The polygon modeling approach is both quicker and involves less complexity with a view to rapidly restore of worn parts. In this paper the process chain for LMD and thereby the functionalities of LACAM3D is presented for a repair application and the near-net fabrication of a BLISK (Blade-Integrated diSK) blade direct from the CAD model.

### 2. LMD repair

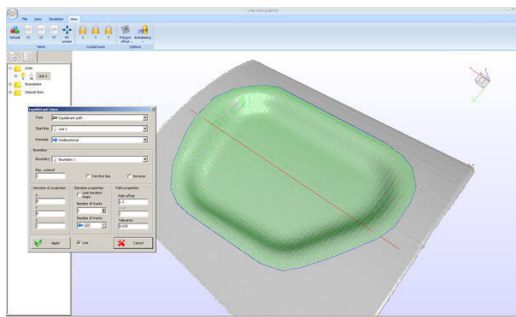
Most parts no longer correspond to the geometry data specified in the CAD data record after usage or due to their manufacturing tolerance. On that account and because there is a need to handle manual prepared welding areas the feasibility to construct a CAD model of the welding area of the part in the clamped state is required. For this reason a laser line scanner was integrated in the LMD system to use it as measuring machine (Fig.1). From the resulting point cloud a polygon mesh is derived and made available in the so called stl format as input for LACAM3D. In general the mesh is unstructured and not cross-linked. In order to realize short computing time for the different CAD

functionalities on the mesh a suitable topology was introduced. This topology allows a fast access on the neighborhood of any point on the geometry.



**Fig. 1.** Laser line scanner

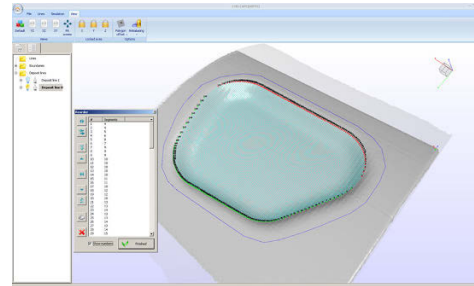
The goal of the LMD repair process is a dimensional accuracy of about 0.5 mm concerning the target geometry. That reduces the post finishing processing substantially. In order to achieve that objective the tool paths of the different layers have to be trimmed at the target geometry i.e. at the so called Master geometry. The Master geometry is a CAD surface model of the non-worn part which includes the welding area. The Master geometry is updated with outside by a best fit to the digitized part model. The part geometry and the Master limit geometrically the deficit volume with outside of about 0.5 mm.



**Fig. 2.** Boundary line of welding area (blue), first line (red) and the group of equidistant lines on the free form surface derived from the first line.

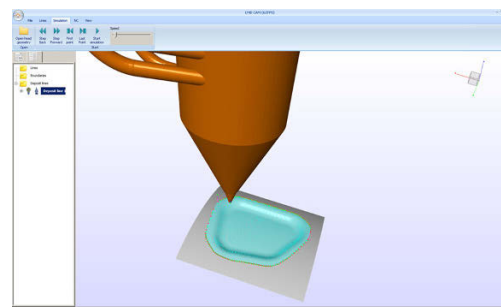
The digitized part and the Master geometry are provided for LACAM3D in the stl format. For the generation of tool path pattern for the first layer the welding area have to be geometrically limited by a boundary line (Fig.2). The fill pattern with equidistant lines is derived from a start line. This line may be a part of the boundary line or has to be defined by LACAM3D. In the simplest way this

line is defined by two points. This line segment is then projected onto the part geometry whereby the projection direction can be freely selected. The equidistant lines are then generated on the part geometry relative to this projected line in both directions. The equidistant lines are trimmed with the boundary line. The number of points per line can be reduced by i.e. thinning out in a desirable precision.



**Fig 3.** Welding area (trough machined into shaft), Master geometry (25% Opacity) and tool path of the 8. Layer.

For this LACAM3D provides a menu from which the different option for tool path generation can be selected (Fig.2). Even at before equidistant line generation the user can determine a uni- or bidirectional path pattern. Via a window menu LaCam3D offers functionalities to change the numbering and direction of each track and to configure the laser energy and scanning velocity for the tool paths (Fig.3).



**Fig 4.** Welding area (trough machined into shaft), Master geometry (25% Opacity) and tool path of the 8. Layer.

The generation of the tool paths of the next layers is based on an offset calculation. In order to fill the trough by LMD with a high dimensional accuracy the displaced tool paths from the first layer are trimmed with the Master geometry.

LACAM3D provides a simulation tool for the inspection for potential collisions between laser head and part geometry (Fig.4). For the generation of cnc code LACAM3D uses a post processor which is customized for the different machining systems.

Fig. 5 shows the trough and the process during LMD repair on basis of the ILT process chain





Fig. 5. Part, welding area und process photo.

### 3. LMD direct manufacturing

For the LMD manufacturing of turbine components (Fig.5) the CAM program is provided with special module.

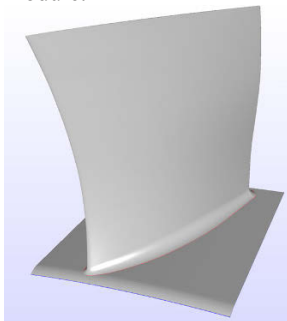


Fig. 6 (a). CAD model of the blade

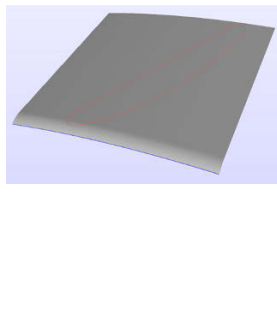


Fig. 6 (b). Part of the outer periphery of a rotor disk.

Due to the considerably varying blade thickness the LMD process requires in dependence of part height different welding strategies. In the root area the blade exhibits a mean thickness of about 8 mm. The outer periphery of a rotor disk, on which the blade is fixed, represents a free form surface (Fig. 6b). For the manufacturing of the blade by LMD layer by layer the blade geometry has to be sliced with the in z-direction displaced surface part of the outer periphery of the rotor disk to determine the welding boundary (Fig.7). To do this LACAM3D offers a functionality to calculate the intersection of any two free form surfaces.

In the following a midline is derived for the boundary line (Fig.7 left) and a group of equidistant lines is generated which are trimmed with the boundary line (Fig. 7 right). The numbering of the lines and the starting point of the contour path can be modified. The root area requires a meander-like filling pattern (Fig.7 right) For the upper layers the boundary line becomes continuously smaller [Fig. 8 (a),(b)]. The variation of the blade thickness becomes lower than 4 mm [Fig. 9 (a),(b)]. In preliminaries studies [1] process diagrams (Fig.19) have been developed which describe the laser power, scanning velocity and beam diameter along the tool path in order to realize tracks with varying thickness but

constant track height. For the generation of cnc code this process diagrams have to be provided to LACAM3D as a discrete measure curve. Depending on the local blade thickness LACAM3D adjusts the process parameters along the tool path according to the processing diagrams.

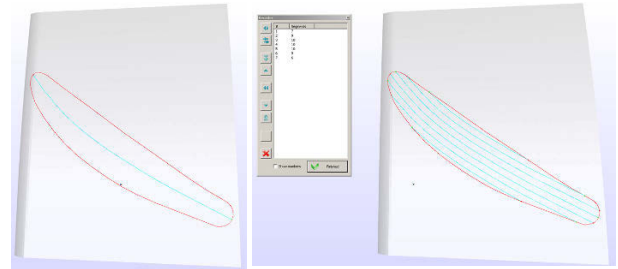


Fig. 7. Contour line as cutting line between blade surface and the outer periphery of a rotor disk and midline in the blade root area (left). Equidistant lines to midline trimmed with layer contour (right).

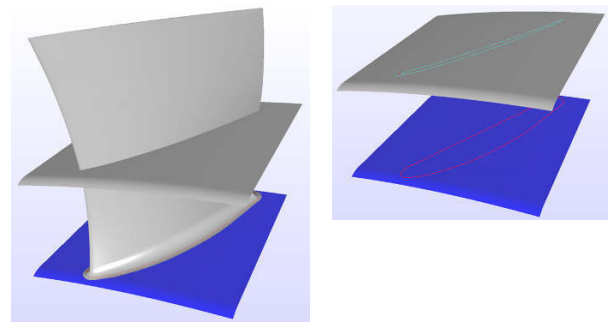


Fig. 8. Part of the outer periphery of a rotor disk and it's vertically offset (left). Contour of two different layers. (right).

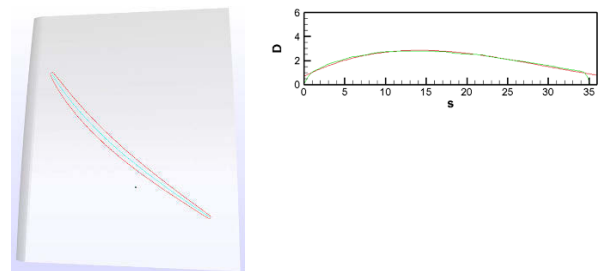


Fig. 9. Contour line as cutting line between blade surface and the outer periphery of a rotor disk and midline out of the blade root area (left). Blade thickness along arc length of the midline (right).



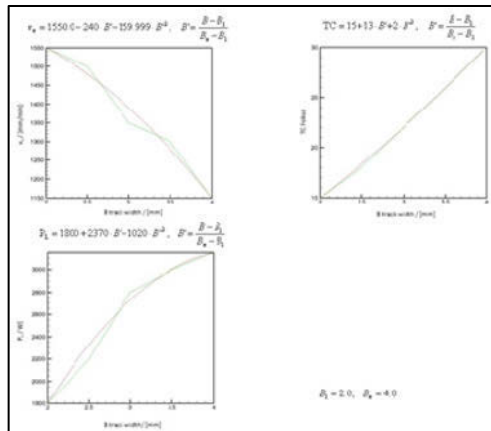


Fig. 10. Process diagrams

Figure 11 shows the resulting blade which has to be finished by milling. The LMD process was adapted in such way that the blade exhibits an oversize of 0.5 mm.

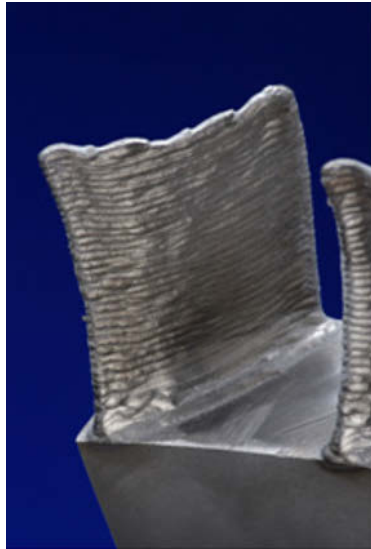


Fig. 11: Blade bevel post finishing.

#### 4. Summary and conclusion

LACAM3D is an offline cam program for LMD equipped with functionalities which enables the user to transfer also complex welding patterns in cnc code just in time. The CAM program has a modular structure so that new welding strategies can be easily added by customer inquiry. At time a prototype version of the program exists and is used for the cnc code generation for different applications for LMD and is under continuously development.

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Proceedings of the 37th International MATADOR  
Conference

Hinduja, S.; Li, L. (Eds.)

2013, XVIII, 450 p., Hardcover

ISBN: 978-1-4471-4479-3