Optimization of Machining Time using Feature Based Process Planning

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Abstract

Planning for machining sequence can be considered as one of the most important functions of manufacturing process planning. However, less attention has been paid to automation of this function in contemporary computer-aided process planning systems. This paper describes an efficient algorithm for automatic machining sequence planning in 2.5D milling and drilling operations. It is programmed in Visual C# and forms the machining sequence planning module of a CIM system. This module is integrated with a feature-based design system that determines required machining operations and parameters for each machining operation. This information is then sent to the machining sequence planning module for determining proper machining sequence plans for producing the part. The algorithm generates feasible machining sequences and optimizes it based on machining time. The algorithm results in minimized tool changes.

Keywords:CAPP, CAM, CAD, STEP

1. Introduction

Machining time optimization in CNC programming plays an important role in manufacturing process planning and scheduling. It is one of the most important deciding factors for cost estimation by NiaziA et al. Product designers can improve and optimize the design of products based on machining time estimation in order to shorten manufacturing cycle and reduce costs. For production engineers, machining time estimation is a critical step towards an optimal and practical production plan. The timeliness and efficiency of such estimation are also critical particularly when we target for outsourcing products quote, real time manufacturing process planning and scheduling systems, when the accuracy of machining time estimation is important for cost estimation and effective process planning.

However, it is difficult to achieve an accurate machining time optimization of complex parts due to the complexity of NC machining processes, combination of multiple factors, as well as the dynamics of manufacturing environments. NC machining time of a part mainly depends on its geometry information, process plan, NC program, and machine characteristics. Existing commercial software tools and research prototype systems do not fully consider these factors, and therefore they cannot provide accurate estimation. To achieve rapid and accurate estimation, this paper presents a feature-based method for NC machining time optimization. There is no general accepted definition of the feature in manufacturing. According to Shah *et a*l. features are generic shapes useful in some computer aided application, such as geometry construction, process planning, and Design for X. In this paper, the feature refers to machining feature which contains process information. The information of machining feature includes not only geometry/topology information but also machining process information. Machining process information will be attached to the feature by parameters. Therefore the machining feature information is composed of feature geometry and parameters. Taking the small holder as an example, the machining features can be classified into pocket, hole, profile, slot and so on. Each type of features has its particular machining method and cutting parameters. Features can be used as the carrier of geometry-process information. Note that we use the term ‘‘geometry-process information’’ throughout the paper since we integrate geometry information and process information in the proposed approach.

2. Literature Review

2.1 CNC machining time optimization

CNC machining time optimization methods can be classified into four categories:

(1)*Optimization based on material removal rates:* Yang and Lin believed that the machining time is mainly decided by the volume of the removed material and the estimated time can be roughly computed based on machining features, they proposed a featured-based formula for machining time estimation. Jung proposed a model to estimate machining time based on material removal rates and manufacturing features. Othmani et al. presented a method to calculate 2.5 axis roughing time based on material removal rates. Hbaieb et al. developed an NC machining time estimation model to calculate cutting time of a part by using material removal rates.

(2) *Optimization based on NC program:* This method calculates machining time by considering setting machining feed rates and length of the tool paths. Due to ignoring machine characteristics and CNC system, it can not achieve an accurate estimation. However, a sit is easy to be implemented, this method has been widely applied in commercial simulation software tools, such as Master CAM.

(3) *Optimization based on NC program and machine characteristics:* According to different approaches to obtain machine parameters, various methods in this category can be further classified into two types. In the first type, machine parameters are obtained from machine configuration files, and then used to simulate machining working conditions. Siller et al. proposed a mechanistic approach for cycle time estimation in high-speed milling of sculptured surfaces.

(4) *Artificial intelligence based Optimization methods:* A multi-valued fuzzy set was developed by Jahan et al. to model the uncertainty activity time/cost estimation in flat plate processing. Zhu et al. proposed an approach for constructing a machining time ANN model through a hybrid method. Yang et al. presented a machining time estimation method based on case reasoning and object characteristic list.

The optimization methods based on material removal rates or artificial intelligent can only be applied in rough estimation occasion due to inadequate information. The method adopted by the commercial software tools to calculate machining time by considering machining feed rates and length of the tool paths can achieve higher accuracy than above methods. However, because of ignoring machine characteristics and CNC system, the weakness of this method is obvious. The methods based on NC program and machine characteristics can get much higher accuracy than other existing estimation methods. The drawback of this type of methods is that it does not consider the influence of the machining condition which is related to the geometry-process information. On the other hand, all of these methods cannot satisfy the requirement of timeliness and efficiency. In order to address this challenging issue, a new feature-based machining time optimization method is proposed in this paper.

2.2 Real-time adjustment

To ensure the efficiency in machining process, machining speed needs to be adjusted in real-time, so estimated machining time should take this into account. One adjustment mechanism proposed in the literature is the force-based feed-rate adaptive method by Kurt M, Bagci E. The key question is the prediction of cutting force. A lot of work has been done in this field. A cutting force prediction method is presented by Zhang and Zheng and a theoretical formula is structured in the literature. In the formula, variables are cutting speed, cutting depth, cutting width, and some correction coefficients. The cutting speed is calculated according to the value set by NC program and machine tool characteristics. The cutting depth is extracted from related feature information. In the cutting process, actual cutting width is different from the value set in the feature, and needs to be calculated according to machining status. Cutting allowance and corner radius should be considered to calculate actual cutting width. In this paper, the actual cutting width is calculated according to the method presented in Hinduja S, Ma YS.

3. CNC Machining Time Impact Factors Analysis

NC machining time impact factors can be classified into four types, which are: the motion information represented or set in NC program, machine performance, interpolation method and machining condition. The direct factor related to NC machining time estimation is the machine speed which depends on a number of factors. The first factor is the control speed set in the NC program, also the length of each individual NC machining tool path block and the turning angle from one tool path block to another is included in the NC program, which is also very important to NC machining time. Other factors include machine performance parameters like maximum speed, maximum acceleration, speed change rules, and acceleration change rules. Meanwhile, real time machine performance depends on the directional change of the tool path. NC machining process is the process of interpolation. Different methods of interpolation cause different kinds of machine speed changes. During the machining process, cutting force varies from cutting conditions. Required cutting force can be calculated according to cutting force and cutting speed. If the required force exceeds the force that the machine can provide, the machine will automatically adjust its speed to ensure working properly.

As discussed above, NC machining time is estimated based on machine characteristics, NC program information, interpolation methods, and cutting conditions. Tool path planning is closely related to relevant machining feature. Each machining feature type has a corresponding tool path planning strategy. Required cutting force is dependent on cutting tools, cutting speed, cutting depth, and cutting width. Cutting speed can be adjusted according to actual machine conditions; while cutting depth and width reflect the cutting condition of the part, which are pre-set based on machining features and cannot be adjusted in real time. However, actual cutting depth and width are not the same as the value pre-set, which change in different positions of the feature; and therefore they should be estimated based on the feature.

4. Proposed CNC Machining Time Optimization Method

4.1 Framework for proposed CNC machining time optimization

As mentioned above, since machining time optimization depends on multiple factors including geometry-process, machine and NC program, it is difficult to integrate all of the factors for machining time optimization. At present, the NC machining information description is mainly by NC program, while NC program only contains movement information and cannot represent geometry-process information. This paper proposes the CNC machining time optimization model based on machining features. Regarding machining features as the carrier of machining knowledge, the proposed model integrates part geometry, process plan, machine characteristics, and NC program effectively, as shown in Fig. 1.

The proposed framework consists of three levels, namely data preparation level, data level and data calculation level. Data preparation level has the function of preparing data for machining time estimation, preparing geometry-process information and NC program information. Geometry-process information is generated through process planning which is rule-based. Machining process template is used for process sequence, required machine tool and cutting tool. At the same time, cutting parameters database is used for cutting parameters decision. The geometry information is transferred by feature reorganization. NC program is generated based on feature-based auto-programming, which will be described in detail in Section 4.4.

The data level consists of three main modules, namely the geometry-process information, machine characteristics, and NC program. These three modules are integrated through specific interfaces: the machine tool identification is the interface between geometry-process information and machine characteristics modules, also it is the interface between NC program and machine characteristics modules; the feature code is the interface between geometry-process information and NC program. In geometry-process information module, each feature is coded by a unique feature code. The feature code is also stored in the NC program in

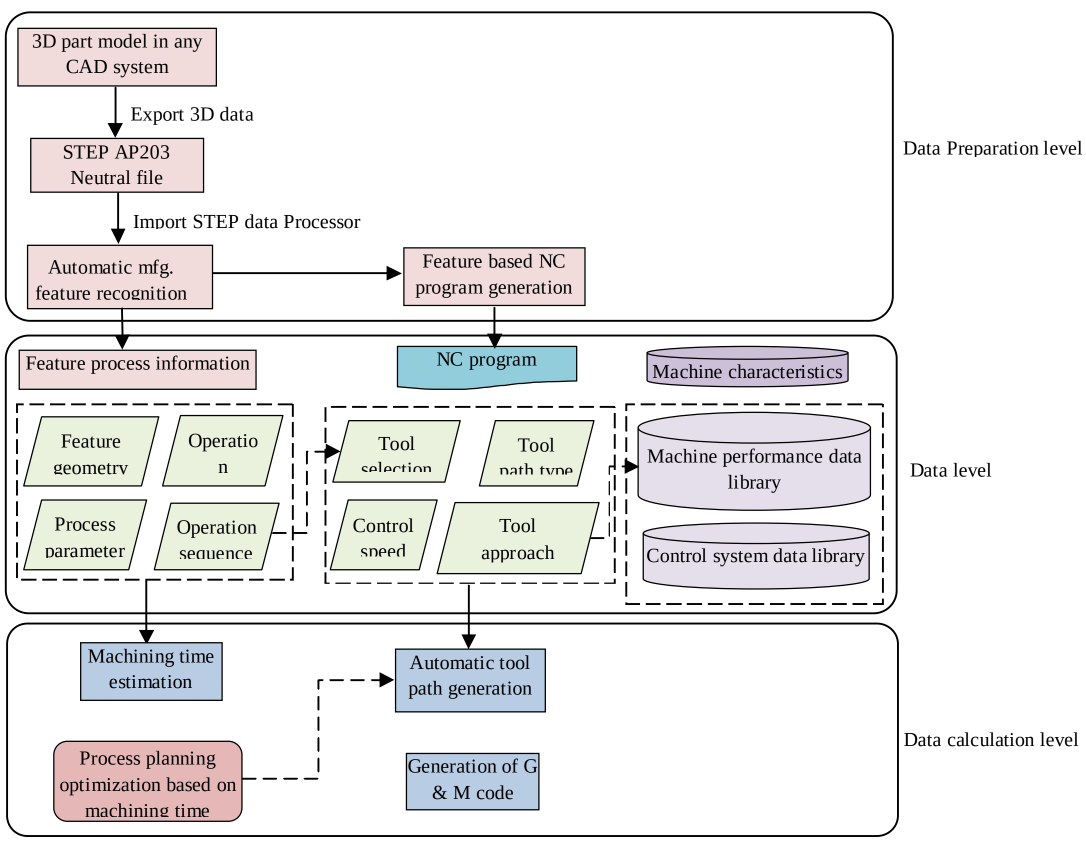

Fig. 1 NC machining time estimation frame

addition to machining information. NC program is organized by features. Each feature has its NC codes. In the process of machining time estimation, geometry-process information is used as the baseline, and all required information is called in the order of process–step–feature. The information flow is facilitated by the interfaces. Geometry-process information, NC program information and machine information are integrated and well organized into an information chain through machine coding and feature coding, so that the information integration problem for NC process machining time estimation is solved effectively.

Data calculation level calculates the machining time using information from data level, and the data level begins with geometry-process information. The machining time of a process is composed of all machining times of the steps of the process, which is expressed as follows:

$$T_p = \sum_{i=1}^{m} T_{stepi} \qquad (1)$$

T_p represents the machining time for the process; T_{stepi} represents the machining time of step i; and T_{stepi} is expressed as follows:

$$T_{stepi} = \sum_{j=1}^{n} T_{mfi} \qquad (2)$$

T_{mfj} represents the machining time for the feature j within one step.

The tool path for a machining feature includes rapid locating, approaching and retreating, and cutting. So the machining time of a feature includes rapid locating time, approaching and retreating time, cutting time, which is expressed as follows:

$$T_{mfj} = t_{rj} + t_{arj} + t_{mj} \qquad (3)$$

t_{rj} represents rapid locating time for feature j; t_{arj} represents approaching and retreating time j; and t_{mj} represents cutting ime j. So the machining time of a machining process can be expressed as follows:

$$T_p = \sum_{i=1}^{m} \sum_{j=1}^{n} T_{mfij} \qquad (4)$$

T_{mfij} represents the machining time of the feature j within the step i.

4.2 Feature-based rapid NC programming

Regarding feature as the carrier of NC machining process knowledge and experience, features can inherit the process parameters and processing strategy. Through the process tem- plates of typical parts, process planning can be realized. After feature recognition by Li YGet al., NC program can be automatically generated based on feature. The accuracy of feature recognition and tool path generation is the guarantee of the accuracy of feature-based NC program rapid generation. Because the machining time estimation is executed based on NC program, to ensure the timeliness, NC program must be generated in a fast way.

The feature-based NC program rapid generation systemdeveloped by the authors has been applied well in a medium scale enterprise for tool holder parts, and achieved an accuracy of 87% for feature recognition and tool path generation. For the features which are not recognized or not correctly recognized, tool path not generated or not correctly generated, the machining time of the feature is estimated based on material removal amount.

There are three advantages through using feature-based NC program rapid generation for machining time estimation:

(1) The machining parameters and machining strategies utilized by feature-based rapid NC programming system are optimized by expert NC programmer. Since the tool path generated is also optimized, the randomness in NC process programming can be avoided, and therefore the accuracy of the machining time estimated based on feature can be improved.

(2) Since feature-based NC program rapid generation can be done automatically, repeated manual operation can be eliminated, and therefore the process planning process becomes much more efficient. Take a 60x60x20 mm^3 small holder part as an example, automatic programming only takes about 2h but manual programming takes about two weeks. But for traditional manual NC programming, it may take at least two weeks.

(3) Because the accuracy requirement of the tool path for machining time estimation is not high, it does not need to consider intervention, over cutting and less cutting, so the simulation validation does not need to be done repeatedly. It is also an important aspect of timeliness guarantee.

4.3 Geometry-process information

Geometry-process information is organized through a kind of knowledge base which consists of machining sequence, machining parameters, machining steps, and machining features. Feature position is used to record its orientation, and is composed of coordinates of several key positions, such as feature center position, corner position, the highest position, the lowest position, and so on. Feature position is the basis of cutting depth and cutting width. Machining allowance, cutting depth and cutting width determine cutting condition. Tolerance, cutting accuracy, and tool path interpolation arehighly interrelated. A small tolerance demands a high cutting accuracy. The higher the cutting accuracy, the more the interpolation points, and the more the polygonal lines. Polygonal lines cause machine speed changes, particularly in corner areas. Some geometry information must be considered, such as corner radius, because most of speed changes happen in the corner area, and the speed changes may be predicted more accurately and conveniently if the corner radius is known. Feature, as the carrier of machining knowledge, can be expressed as follows:

$$MF = (FC, FP, MA, AP, AE, Tol, Geo) \quad (5)$$

MF represents machiningfeature, *FC* for featurecode, *FP* for feature position, *MA* for machiningallowance, *AP* for cutting depth, and *AE* for cuttingwidth, *Tol* for tolerance, *Geo* represents geometry informationsuchascornerradius.

4.4 NC program

This paper proposes a new method of organizing NC program information. NC program is organized by machining feature as unit.

4.5 Machine characteristics

Machine characteristics are also stored in data library, including three parts: machine library, CNC system library, and speed control mode library. Machine library includes machine names, numerical control systems used by the machines, machine performance parameters such as maximum force, maximum speed, and maximum acceleration.

4.6 Machining time calculation

In order to compromise between machining time estimation accuracy and estimation efficiency, different factors are considered according to different characteristics of the machining types. For roughing and drilling, because they are low speed machining, calculated machining time based on tool path length and control speed is very close to the actual machining time, therefore it is better to simply use a correction coefficient. In a finishing phase, it is high-speed machining for most of the time, and the impact of machine characteristics to machining time is remarkable, and there is a big difference between the calculated machining time and the actual machining time, therefore it should consider the impact of machine characteristics, geometric information, and tool path information.

The tool path of each feature is usually composed of rapid locating, approaching and retreating, and cutting. Rapid locating tool path is very simple, and the time can be calculated as discussed above. Approaching and retreating tool path is relatively complex. If machine characteristics are used to calculate machining time, it will be inefficient. Because approaching and retreating tool path is part of the strategy for tool path planning, it is related to feature-based knowledge.

5. Case study

A prototype system is developed on the platform of visual C# based on the proposed method. The prototype system includes a geometry-process information structuring module, an NC programming module, a machining time estimation module, and a machining knowledge database. The machine characteristics are captured in the machining knowledge database. The cutting condition and

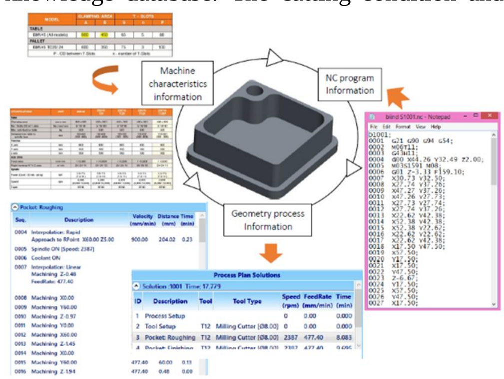

Fig.2 The application case of a small holder part

its influence are implemented in the estimation module as an algorithm. The files generated by the system include an NC code information file and a geometry-process information file. Themachining time calculation is executed based on these files and the machining knowledge database in the machining time calculation module.

Table 1 The resultsofmachiningtimeestimationofthepart

Operation	Operation description	Actual machining time (min)	Estimated time using MasterCAM (min)	Error (%)	Estimated time based on NC program and machine characteristics (min)	Error (%)	Estimated time using proposed method (min)	Error (%)
Roughing	External profile milling	2.0	1.4	-30.0	1.8	-10.0	2.4	20
	Bottom corner milling	2.3	1.6	-30.4	1.9	-17.4	2.5	8.7
	Inner pocket milling	7.7	6.2	-19.5	7.9	2.6	8.0	3.9
Finishing	External profile milling	2.1	1.3	-38.1	1.8	-14.3	1.9	-9.5
	Bottom corner	1.1	0.8	-27.3	1.0	-9.1	1.3	18.2

	milling							
	Inner pocket milling	1.4	0.8	-42.8	1.6	14.3	1.6	14.3
Drilling	Corner hole	1.2	1.0	-16.7	1.1	-8.3	1.4	16.7
Average		--	--	-29.3	--	-6.0	--	10.3

As shown in Fig. 2, this section presents a case study on the NC machining time estimation of the small holder test part in order to illustrate how the prototype system works and to compare the accuracy of the proposed NC machining time estimation method against other methods. The scale of the part is 60x60x20 mm^3.

In the present case study, the process plan of the test part and related NC program are created by feature-based NC program rapid generation module. Machine parameters and characteristics are obtained from a machine configuration file. Machining time of each individual step is calculated by the prototype system. The related UI is shown in Fig. 2. The estimated times by the proposed method and actual machining times for all the required steps are shown in Table 1. In order to demonstrate the advantages of the proposed method, we compared the proposed method with two other methods: MasterCAM, NC program and machine characteristic-based approach. As shown in Table 1, it is evident that the proposed method has a much higher accuracy than MasterCAM and the NC program and machine characteristic-based approach.

6. Conclusion

A prototype of NC machining time estimation system based on the proposed feature-based model has been developed, and tested in a small scale manufacturing enterprise. Experiment results show that the proposed approach is feasible and practical.

The proposed approach considers the influence of geometry-process information to cutting speed and it is integrated with NC programming and machine tool information. Since the cutting speed can be predicted more precisely, the machining time can be estimated more accurately.

Compared with other commercial tools and research prototype systems, our feature-based NC machining time estimation system has a higher accuracy because it considers geometry-process information, local speed changes and speed optimization. Additional strategies have been taken to ensure not only the high accuracy but also the high efficiency.

Significant efforts are still required to improve the proposed approach. Our short term goal is to improve the rapid and automatic programming.

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