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Technical Paper

An innovative approach for automatic generation, verification and optimization of part programs in turning

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ABSTRACT

Continuous innovation of products and optimization of manufacturing processes are of fundamental importance for preserving competitiveness. In the last decades, several approaches based on analytic models for optimization of basic machining operations such as cylindrical turning and face milling have been developed. However, the analytic approaches may not be adequate for real industrial applications, since they are based on average cutting parameters and thus they are not capable of taking into account the effect of complex geometries and instantaneous cutting conditions. In this paper, an innovative integrated system for automatic generation of optimized part programs in turning based on realistic machining simulation is proposed. The system components are described in detail and the machining simulator is validated by comparison with the results of real cutting tests. Then, the optimization approach is applied to a simple case study. The results show that the behavior of the cost function is rather complex, even for simple workpieces. Moreover, the simulator can detect unfeasible combinations of cutting parameters and thus reduce inline part program refinement and optimization. The optimal combination of cutting parameters determined by the new system was competitive with the solutions derived from tool specifications or proposed by a machining expert.

1. Introduction

Nowadays, competitiveness of manufacturing enterprises is maintained through continuous innovation of products and optimization of the manufacturing processes. This is of fundamental importance in order to minimize the production costs and maximize the productivity by concurrently assuring the required product quality.

Optimization of machining processes is a key step for enhancing the performance of manufacturing enterprises dealing with high-precision mechanical parts [1]. Specifically, optimization targets may be achieved by accurate and reliable estimation of machining time and production cost of each elementary operation.

1.1. State of the art on the optimization of parameters in turning

In the last decades, several analytical approaches aimed at determining optimal cutting parameters for basic machining processes such as turning, milling, grinding and many others have been developed [2,3]. Many authors proposed single pass and multi-pass optimization strategies for turning processes, as illustrated in Table 1.

One of the first cost models for strict economic analysis of machining operations was proposed by Gilbert in 1950 [24]. Since then, several approaches were proposed in literature for time and cost estimation in machining, however they are not radically different from this archetypal model. Specifically, model adaptation to multi-pass turning was developed by Shin and Joo [4] and later refined by Chen and Tsai [6]. The optimization methodology included important technological constraints, affecting the admissible cutting parameters ranges, such as the maximum cutting power, surface roughness and others.

In the following years, similar analytical approaches for time and cost evaluation were adopted by other authors with minor improvements, in order to adapt the model to slightly more complex turning profiles [10,11] provided that they can be decomposed into a set of straight, tapered and circular segments.

Generally, the production cost, the machining time and their combinations were the target functions of optimization methods, as shown in Table 1.

It should be pointed out that these approaches were not based on estimation of instantaneous cutting conditions or simulation, but on averaged cutting parameters for each cutting pass.

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Table 1
State of the art on optimization of turning operations.

Ref.	Machined workpiece geometry	Target function	Mathematical model	Optimization method
[4]	Cylindrical	a	Self	Dynamic Programming
[5]	Cylindrical	b	[4]	Analytical
[6]	Cylindrical	a	Self	Heuristics
[7]	Cylindrical	a,b	[6]*	Random Search
[8]	External profile with multiple diameters	b	[6]*	Heuristics
[9]	Cylindrical	a,b	[6]*	Analytical
[10]	External straight, tapered and circular profiles	a	[6]*	Heuristics
[11]	External profile with multiple diameters	a,b	[6]*	Polynomial Networks
[12]	Straight internal and external profiles	a	[6]*	Heuristics
[13]	Longitudinal turning	a	[6]	Heuristics
[14]	External straight, tapered and circular profiles	a	[6]	Heuristics
[15]	Cylindrical	a	[4]	Heuristics
[16]	Cylindrical	b	[6]*	Sequential Quadratic Programming
[17]	Straight internal and external profiles	a	[6]	Heuristics
[18]	Cylindrical	b	[6]*	Heuristics
[19]	External straight, tapered and circular profiles	a,b	[6]*	Analytical
[20]	External straight, tapered and circular profiles	a,b	[6]	Heuristics
[21]	Cylindrical	a,b	[6]*	Heuristics
[22]	Cylindrical	a	[6]	Heuristics
[23]	Cylindrical	a	[6]*	Heuristics

*: with minor improvements; a: production cost; b: machining time.

Similarly, process outputs – such as the surface roughness or cutting power – were derived from theoretical mathematical models based on averaged cutting parameters. Due to this strong simplification, these approaches are not sufficiently reliable when dealing with real industrial applications which require a higher degree of sophistication and realism.

1.2. Proposed approach

The present situation concerning production planning and design is illustrated in Fig. 1(a). The key actors in this process are the machining expert(s), the CAM software and, later, the machine tool. It is an expensive procedure since the machining expert is involved in all the process-design phases such as selection of machining strategies, tools, machining parameters, part program generation, geometric simulation and post processing. Moreover, the NC code should usually be refined and tested on the machine tool, which is extremely expensive due to the high hour cost of the machine tool and the loss of gain due to missed production.

Therefore, the development of an integrated system for automatic generation, preliminary verification and optimization of part programs is of great interest, see Fig. 1(b). The application of these automatic systems may indeed drastically reduce the machining expert working hours and the time needed for setting-up the production process at the machine tool.

The paper presents an integrated system for preliminary machining time and production costs optimization based on the simulation of multi-pass turning operations performed on generic workpiece profiles.

The system consists of: (1) an automatic tool path generation and post processing module which generates the part program and interfaces with the simulator; (2) a machining simulator which predicts the physical behavior of the cutting process and its exceptions; (3) an optimization module based on the gradient descent principle. Machining time, production cost and feasibility of the considered cutting conditions are determined from the simulated data.

The paper is organized as follows: an overview of the proposed system together with its implementation details are given. Afterwards, the machining simulator is experimentally validated through comparison with real cutting tests. Last, a relatively simple case study was numerically investigated, in order to study the behavior of the cost function and to evaluate the effectiveness of the optimization algorithm.

2. Automatic part program generation and optimization

The detailed architecture of the integrated system is given in Fig. 2.

The inputs of the system are:

1 workpiece geometry database, composed by the list of segments and circular arcs representing the longitudinal section of both the raw workpiece and the final workpiece;
2 the fixture geometry database, including the list of segments and circular arcs representing the chuck and fixtures of the lathe;
3 machining strategies database which consist of an index of available machining strategies composing the working cycle;
4 the inventory of tools available for machining, including their geometries and technological specifications;
5 other parameters such as simulated machine tool characteristics, mathematical models for tool wear and roughness evaluation, cost function coefficients and other machining constraints.

All the inputs are stored into XML files designed for the purpose.

For example, the finished and raw workpiece profiles are basically geometry database tables, as shown in Fig. 3. Each table consist of a list of segments and circular arcs defined by: start and end coordinates, type of the element (1 = linear, 2 = circular clockwise, 3 = circular counterclockwise) and arc center. These tables are semi-automatically generated in Mathworks Matlab programming environment using specific geometrical computation functions and starting from a list of construction points derived from part drawing.

The outputs of the system are the optimized part program, the list of tools, the optimized cutting parameters and the inspection results contained into an XML database.

2.1. NC code generation

The trajectory generation module computes the multi-pass and multi-tool trajectory composed of a sequence of segments and circular arcs and according to the sequence of machining strategies, tool geometry and selected cutting parameters.

The elaboration of the tool trajectory is based on computational geometry algorithms, such as those present in modern CAM systems, implemented in Matlab. They are based on the profile offset