Mathematical Modeling for Reconfigurable Process Planning

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Abstract
The paradigm shift in manufacturing systems and their increased flexibility, and changeability require corresponding responsiveness in support functions to achieve cost-effective adaptability. Reconfigurable Process Planning (RPP) is an important enabler of changeability for evolving products and systems.
Mathematical programming and formulation is presented, for the first time, to reconfigure process plans to account for changes in parts' features beyond the scope of the original product family. Reconfiguration of precedence graphs to optimize the scope and cost of process plans reconfiguration is achieved by inserting/removing features iteratively using a novel 0-1 integer programming model. The proposed RPP mathematical scheme scales better with problem size compared with classical process planning models. The formulation of the mathematical model at each iterative step of reconfiguration has been automated. A process plan reconfiguration index (RI) that captures the extent of changes in the plan and their implications has been introduced. A prismatic benchmark and an industrial case study are used for illustration and verification. The computational behavior and advantages of the proposed model are discussed, analyzed and compared with classical models.

Keywords:
Computer automated process planning, Mathematical programming, Reconfigurable process planning

1 INTRODUCTION

Manufacturers in the Western world are faced with more challenges due to the fierce competition from emerging new economic powers and open markets that are increasingly revolving around customers needs worldwide. They must continuously develop and enhance their products designs and quality by applying state of the art products and system design methods and adopting cutting edge manufacturing philosophies. Rapid evolution of the current manufacturing systems is witnessed through the advent of new technologies such as Changeable and Reconfigurable Manufacturing Systems (RMS) [Koren *et al.*, 1999].

Reconfigurability aims at achieving more competitiveness by offering enablers in terms of technology and supporting business paradigms [ElMaraghy, 2005]. Reconfiguration could be achieved at the system or machine levels and it may be soft (logical) or hard (physical) in nature. Process planning is an important soft type enabler for such changeable systems. It is a critical function for the operation planning and system design of any manufacturing system. Variant process planning techniques lend themselves to RMS since, like Flexible Manufacturing Systems (FMS), RMS is usually designed for a certain part family but with wider scope. However, generative process planning systems are better able to handle un-planned product variations. Therefore, a hybrid Reconfigurable Process Planning (RPP) system that is variant in nature yet capable of generating process plans for parts with machining features beyond those present in the current part family's composite part can best meet the current challenges [Azab *et al.*, 2006].

In this work, a novel mathematical model for RPP is introduced, where process plan reconfiguration takes place by finding an optimal scheme for inserting/removing features within the prescribed constraints.

2 PREVIOUS WORK

Very few publications have tackled the RPP problem. Zaeh *et al.* [2006] suggested that Agile Process Planning is useful for the production of individualized products and constantly reconfiguring companies. ElMaraghy [2006] classified the various process planning concepts and approaches, based on their level of granularity, degree of automation, and scope. The new concept of "Evolving Parts/Products Families" was introduced. The need for "Evolvable and Reconfigurable Process Plans", which are capable of responding efficiently to both subtle and major changes in "Evolving Parts/Products Families" and changeable and Reconfigurable Manufacturing Systems was indicated.

The most relevant process planning approaches that support, to varying degrees, changeable and agile manufacturing paradigms are:

2.1 Variant Process Planning Systems

Retrieval process planning is confined to changes within the scope of the planned family and its master composite part. Hetem [2003] stated that the variant concept of RPP is increasingly becoming a reality in power-train manufacturing engineering. Feature based process templates may be modified to suit new designs within the family. Bley and Zenner [2005] proposed an integrated variant management concept to meet the continuously changing needs and used features technology and generalized product models.

2.2 Generative Process Planning Systems

In this approach, a new process planning problem is re-solved generatively for every new product configuration. In most literature, a mathematical or rather a procedural method is proposed and solved using either near-optimal optimization methods or heuristics. Xu, *et al.* [2004] presented a clustering method for-multi part operations planning based on analyzing process plans for

Reconfigurable Machine Tools (RMT) design, specified tolerances and concurrent machining requirements. Pattern recognition algorithms for recognizing the similar sub-operation groups within the entire part family was established. Shabaka and ElMaraghy [2005] proposed an approach for selecting different types of machines and their appropriate configurations to produce different types of parts and features, according to the required machines capabilities. The structure of the machine tools was represented as a kinematic chain that showed the number, type and order of different axes of motion on both the tool and the workpiece sides of the machine. More than one minimum machine configuration for a single operation cluster was generated and hence increased the flexibility in machine tool selection and operations assignment. This approach is not limited to RMS, and is applicable to any manufacturing system where dynamic and flexible process planning and machine assignments are required. Azab *et al.* [2006] argued that variant process planning systems, with their rigid definition of part families' boundaries, are not best suited to support RMS and that generative process planning has more potential as an enabler of such technology. However, since purely generative process planning systems are not yet a reality, a semi-generative process planning system was developed where a random heuristic based on Simulated Annealing was exploited.

2.3 Macro-Level Process Planning

Macro-level process planning is difficult because of its dependence on declarative process knowledge including part geometry, tools, machine tools, fixtures and technological requirements and also its implied time-dependency represented by the order in which the given features would be machined. The used optimization criteria range form minimum transportation of parts between and within machine tools to minimum change of cutting conditions and rapid tool-traverse. Lin *et al.* [1998] stated the problem had traditionally been determined through rule-based knowledge that was acquired from machining practices. Most of the available research utilized geometric information and constraints for precedence creation and some of the reported research used multiple factors to determine the precedence constraints for sequencing of operations. Almost all mathematical models developed for the classical macro-level process planning are based on the Traveling Sales-Person (TSP) problem formulation [e.g. Lin & Wang 1993]. Koulamas [1993] formulated the problem as a mixed integer programming model.

There are no mathematical formulations in the literature for the RPP problem. Most of the publications have approached the problem in a traditional manner by generating a complete process plan for each new configuration. This is in fact "Re-planning", but true Reconfigurable Process Planning did not yet materialize [ElMaraghy, 2006].

Process planning was classified according to granularity as well as the degree of automation [ElMaraghy, 2006]. The proposed RPP approach offers genuine reconfiguration and can be classified as semi-generative process planning methodology at a macro-level.

3 RECONFIGURABLE PROCESS PLANNING (RPP) CONCEPTUAL FRAMEWORK

RPP is the development of a process plan for a new part some features of which are not within the boundaries of the existing parts family or its composite part and master plan, i.e. the new part belongs to an evolving parts family [ElMaraghy, 2006]. The master plan would be modified to meet the requirements of the new part and its added features. New portions of the process plan, corresponding to the new additional features (and their machining operations), are generated and optimally positioned within the overall process plan.

If the sequence of features processing, which respects precedence constraints, is thought of as a genetic sequence, the added new features would represent mutation of that sequence by optimally inserting new genes (See Figure 1). This is consistent with the concept of evolving parts families. An innovative mathematical formulation using 0-1 integer programming is presented and algorithms for its automation are proposed. This combined generative/retrieval process plans reconfiguration is summarized as follows:

1. Retrieve the macro-level master process plan for the family's composite part, which contains the collection of feature/operation precedence graphs and their sequence, knowledge of available manufacturing resources (e.g. fixtures and tools) and their sequence.
2. Compare the new part with the composite part to identify new and missing features.
3. For missing features, subtract the fragments corresponding to these features from the master plan.
4. For new/added features, formulate and apply iteratively the proposed mathematical model for generative reconfiguration.
5. For common features, retain the corresponding features graph portions.

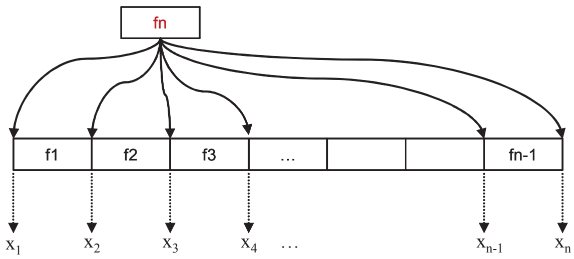

Figure 1: Illustration for finding the best position for a new added feature (f_n) in the master original sequence using the evolving process planning sequence and genetic mutation metaphors.

4 RPP MATHEMATICAL MODELING

The problem of macro-level process planning has long been modeled as a sequencing problem. The concept used in the proposed RPP is totally different. The objective is to determine the best location to insert the new feature(s) in the existing sequence while optimizing objective criteria and without violating specified constraints.

4.1 Assumptions and Notations

The assumptions made in this model are as follows:

1. The considered precedence constraints include:
   a) Accessibility of the feature by the tool.
   b) Logical sequence of operations.
   c) Geometric Dimensioning & Tolerancing (GD&T) constraints.
   d) Non-destruction of completed operations & features.
   e) Machined fixture datum points on the part.
   f) Good manufacturing practices and knowledge.
2. Feature Precedence Graph (FPG) is used to model the interactions and precedence relations, i.e. constraints that exist among the different features. An FPG is a tree-like structure graph where machining features are mapped to nodes and precedence constraints to arcs.

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