Optimum Routing Algorithms for Control Programs Design in the CAM systems for CNC Sheet Cutting Machines

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Abstract. In mechanical engineering, in the production of metal structures and in other industries, a significant part of the products are made from blanks obtained from sheet materials on CNC machines. Special software used at enterprises for the development of NC programs (so-called Computer-Aided Manufacturing, CAM-systems) ensure the automation of the process of the NC programs developing, but do not allow optimize the time and cost of the cutting process. At the same time, when modeling the tool path, CAD users often have to use interactive methods for designing control programs, since the algorithms for generating of programs implemented using the automatic design mode, in many cases do not allow satisfy to many technological requirements for sheet cutting. The paper describes a new approach to solving the Cutting Path Problem (CPP or the Tool Path Problem) in the automatic design mode, which allows taking into account the specific constraints of thermal sheet cutting technologies and solve different classes of Cutting Path Problem. The proposed approach is based on the use of several models of discrete and continuous route optimization, heuristic methods of accounting for technological constraints and the concept of the basic cutting segment. To test the developed optimization algorithms, specialized library of test instances. The results of computational experiments are presented.

INTRODUCTION

The well-known Cutting Path Problem is very difficult problem of continuous and discrete optimization. The mathematical problems of this task are aggravated by technological constraints arising from thermal cutting of parts on CNC sheet cutting machines. Special CAM-systems ensure the automation of the process of the NC programs developing, but do not allow optimize many parameters of the cutting process. The problem of optimizing the tool path the sheet cutting machines is still an urgent problem.

Designing a NC programs for technological equipment of the sheet cutting assumes preliminary geometric modeling of parts and the development of a nesting plan for sheet material. This task belongs to the class of Cutting & Packing problem (C&P) [1]. At the next stage, the process of assigning the route of the cutting tool movement, which generates the optimization problem of minimizing the cost and time characteristics while cutting the parts (the Cutting Path Problem). The tool path is considered specified if the following parameters are specified:

- pierce points (piercings) of sheet material by tool;
- points of switching the tool off;
- tool trajectory from piercing up to point of switching the tool off (the cutting segment);
- Airtime motions/ idling tool path (linear movement from tool switching off point up to the next piercing).

In the cutting segment, there are usually two sub-segments (see Fig 1.):

- lead-in (tool trajectory from piercing up to the entry point on the contours, that are the boundaries of parts);
- lead-out (tool trajectory from exit point on contour up to points of switching the tool off).

In some cases, the point of switching the tool off may be directly on the contour, i.e. the lead-out length equals zero.

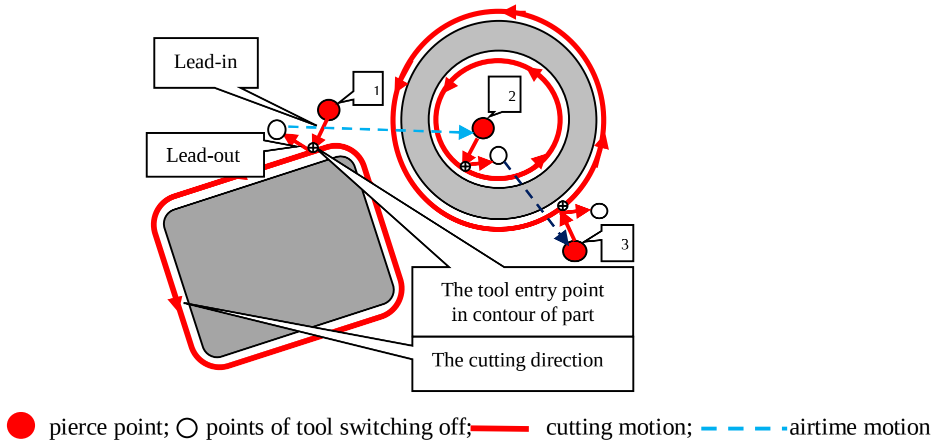


Figure 1. The cutting scheme example for two parts using standard cutting technique

Criteria for optimizing the cutter path are usually the total machining time and cutting cost.

In contrast to standard techniques, special cutting techniques can be used. Special cutting methods include, in particular, "multi-contour cutting" and "combined cut". Multi-contour cutting involves cutting multiple contours within one segment using a single insertion point. The combined cut is used when cutting parts that contain straight line segments in the contour, and which during the cutting process are placed in such a way that they have a common border along one of these straight line segments. The common straight boundary allows you to place parts with a half cut allowance, i.e. a width of the cut, since it is cut only once, which saves material and reduces the total cut length by the amount of the combined cut.

Figure 2 shows an example of a multi-contour cutting scheme for six polygons using the combined cut technique.

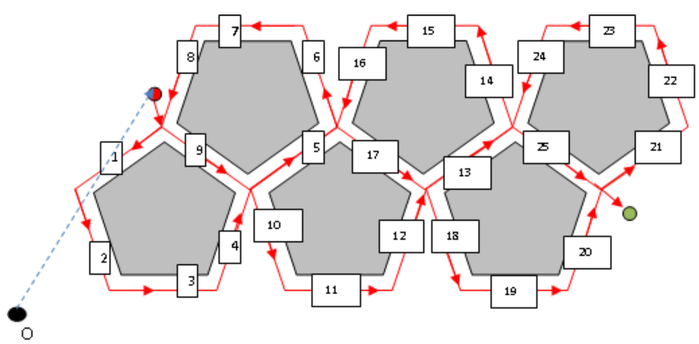


Figure 2. An example of cutting six polygons using one pierce point.

In some cases, the use of special cutting methods makes it possible to reduce thermal deformations and warpage of parts, which occur during thermal cutting of sheet material on CNC machines. Depending on the cutting technique used and the methods for selecting the pierce points and entry points into contour, all tool path tasks are divided into the following classes (some of these classes are named from the corresponding mathematical model used for the solution):

1. TSP Traveling Salesman Problem. Cutting technique is standard for all contours. The entry point into the contour is predefined.
2. The generalized traveling salesman problem (GTSP). Cutting technique is standard for all contours. The contour entry point must be selected from a finite predefined set of points on the contour.
3. The challenge of continuous cutting CCP. Cutting technique is standard for all contours. The contour entry point for each contour can be freely selected.
4. Cutting task with fixed entry points ECP (End Points Problem). The possible entry points for the contours are specified. It is possible to use non-standard cutting techniques, including cutting outlines in parts.
5. The ICP challenge. This task is the most difficult and most common case of a routing problem. There are no restrictions on the choice of points of entry into the contour and the cutting technique used.

A general overview of algorithms for solving the Cutting Path Problem for the above classes is given in [2]. The largest number of publications is devoted to solving the GTSP, since there are many algorithms for solving the classical generalized traveling salesman problem. Among them, one can single out the algorithms described, in particular, in works. [3-10] At the same time, these works do not take into account the technological limitations that arise during thermal cutting of workpieces on machines with numerical control. These restrictions include, in particular, the precedence conditions and the requirements for maintaining the rigidity of the material when choosing the insertion points and forming the tool path of a CNC machine (see, in particular, [11,12]). This fact dictates the need to develop specialized optimization algorithms. A number of specialized algorithms for solving a very narrow class of problems are described in [13-15}. It should be noted that there is practically no description of algorithms for solving ICP problems in the scientific literature.

A new approach to solving the Cutting Path Problem in the most general setting (ICP) is proposed below and the software developed by the authors is described. The approach is based on the concept of the basic cutting segment introduced in [16] and the advanced classification of routing problems, as well as the use of several discrete and continuous optimization models.

GENERAL STATEMENT OF THE CUTTING PATH PROBLEM AND BASIC DEFINITIONS

В соответствии с [16] введём следующие определения.

Definition 1. Segment of cutting (the cutting segment) $\vec{S} = \overrightarrow{MM^*}$ is a tool trajectory from piercing M up to point of switching the tool off M^*. $(S \subset \square \times \square ; M = (x, y), M^* = (x^*, y^*) \in \square \times \square)$

Geometrically, the cutting segment is a curve defined on the Euclidean plane. We will also assume that at each point of the trajectory the direction of movement of the tool is determined.

Let K be the number of segments the tool path consists of.

$\overrightarrow{S_k} = \overrightarrow{M_k M_k^*}; k = \overline{1,K}$. Single segment may contain one contour, a few contours (for the multi-contour cutting), or a part of contour (for multi-segment cutting). Sequence of segments is a permutation $i_1, i_2, \ldots, i_K$, i.e. the ordered set of natural numbers from 1 to K or bijection on a set $\{\overline{1,K}\}$ Thus, the cutting path is defined in terms of the cutting segments by a tuple:

$$ROUTE = \langle M_0, M_1, \overrightarrow{S_1}, M_1^*, \ldots, M_K, \overrightarrow{S_k} M_K^*, i_1, \ldots, i_K \rangle \quad (1)$$

Here M_0 is initial point of tool.

As objective function is most often used the cost of cutting process [17]:

$$F = L_{off} * C_{off} + L_{on} * C_{on} + N_{pt} * C_{pt} \quad (2),$$

where C_{off} is cost of idling tool path unit; C_{on} is cost of working tool path unit; C_{pt} is cost of one piercing, L_{on} is length of the work path, L_{off} is length of the idling path (airtime move) and N_{pt} is number of pierce points N_{pt}.

Definition 2. Basic segment $B^S, j = \overline{1,N}$ is a part of segment $\vec{S} = \overrightarrow{MM^*}$ without lead-in trajectory and lead-out trajectory.

Let's consider that unlike a cutting segment the corresponding basic segment has no direction of cutting, i.e. it contains only geometry information

By definition $\overrightarrow{S_j} = \overrightarrow{\langle lead_{in}{}^j, B^{S_j}, lead_{out}{}^j \rangle}$ but since the basic segment has no direction, then when basis segment contains one or more closed contours, direction of cutting (“+” for clockwise, “-” for counter clockwise) must be specified for each of them.

Every basic segments contains list $L(B^{S_j})$) of its closed contours (may be empty). Let $|L(B^{S_j})|$ is length of this list. Then

$$\overrightarrow{S_j} = \langle lead_{in}{}^j, B^{S_j}, p_j^1, \ldots p_j^r, \ldots p_j^{|L(B^{S_j})|}, lead_{out}{}^j \rangle, \quad (3)$$

where $p_j^r = \pm 1$ - cutting direction, $j = \overline{1, K}$.

Formulas (1) - (3) give the most general mathematical definition of The Cutting Path (Route) for CNC sheet cutting machines.

Definition 3: SCCP (Segment Continuous Cutting Problem) is a problem with fixed number *K* and fixed set of basic segments B^{S_k} $k = \overline{1, K}$.

Suppose that for the initial problem a finite set of the basic segments sets is fixed (an ensemble of base segments of dimension *T*). This ensemble corresponds to ensemble of $\{SCCP_i \mid i = \overline{1, T}\}$

Definition 4: GSCCP (Generalized SCCP) is $\{SCCP_i \mid i = \overline{1, T}\}$

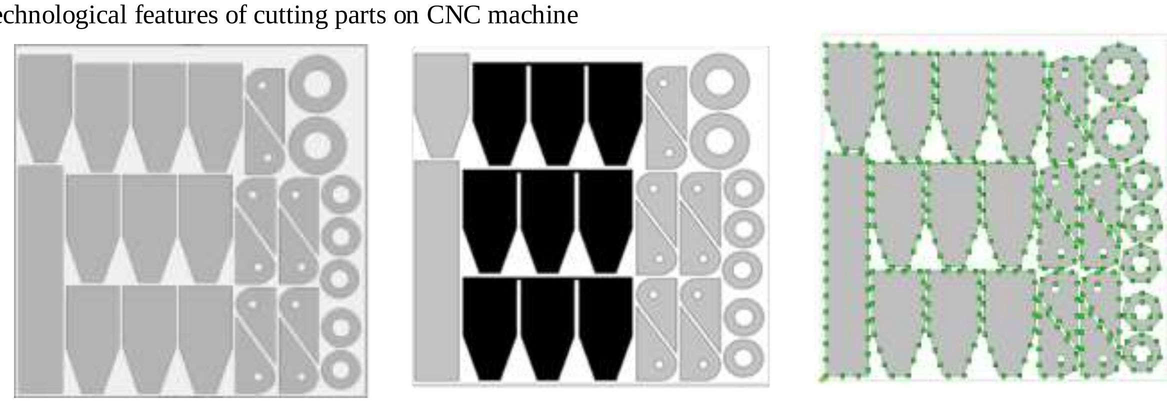
Thus, by introducing the class of GSCCP, we have significantly expanded the existing classification of tool path problem for CNC sheet cutting machines. Actually SCCP and GSCCP are subclasses ICP containing all tasks with finite sets of basic cutting segments, i.e. $CCP \subset SCCP \subset GSCCP \subset ICP$. As the author's best knowledge, no attempt has been made to solve the tool path problem as ICP.

Thus, in ICP class has been selected the big class of cutting path problems for which it is possible to develop the effective optimization algorithms.

GENERAL SCHEME FOR SOLVING GSCCP. ALGORIYHMS FOR SOLVING THE CUTTING PATH PROBLEM

The following solution scheme is proposed.

Each task with a fixed (K_i) set of basic segments $\left\{B^{S_j}\right\}_i$ $j = \overline{1, K_i}$ $i = \overline{1, T}$ resolved independently of the others. Among all the solutions found, the solution with the minimum value of the objective function (2) is selected. Each set of basic segments can be represented by its discrete variant for applying discrete optimization algorithms. An example of a GSCCP task and sampling of sets of base segments is shown in Fig. 3. In Fig. 3a and 3b show sets of 45 and 39 base segments, respectively, for 28 parts, the boundaries of which are defined by 45 contours. The first set of base segments $\left\{B^{S_j}\right\}_1$ (Fig. 3a) coincides with the set of boundary contours, i.e. K_1 = 45 in the second set (Fig. 3 b) 9 parts (highlighted in black) will be cut using the multi-contour cutting technique, three parts in each row. They correspond to three basic segments. Thus, the total number K_2 of basic segments $\left\{B^{S_j}\right\}_2$ is 39 and the total number of SCCP tasks is *T* = 2. An example of discretization the base segments for each SCCP task by 425 points is shown in Fig. 3 s). The selected points (and only they) can be used as points of entry of the tool into the basic segment. Thus, both tasks are reduced to the GTSP model with some additional restrictions caused by the above-mentioned technological features of cutting parts on CNC machine



a) b) c)

Figure 3. Discretization of 45 and 39 base segments by 425 points for enter into basic segment.

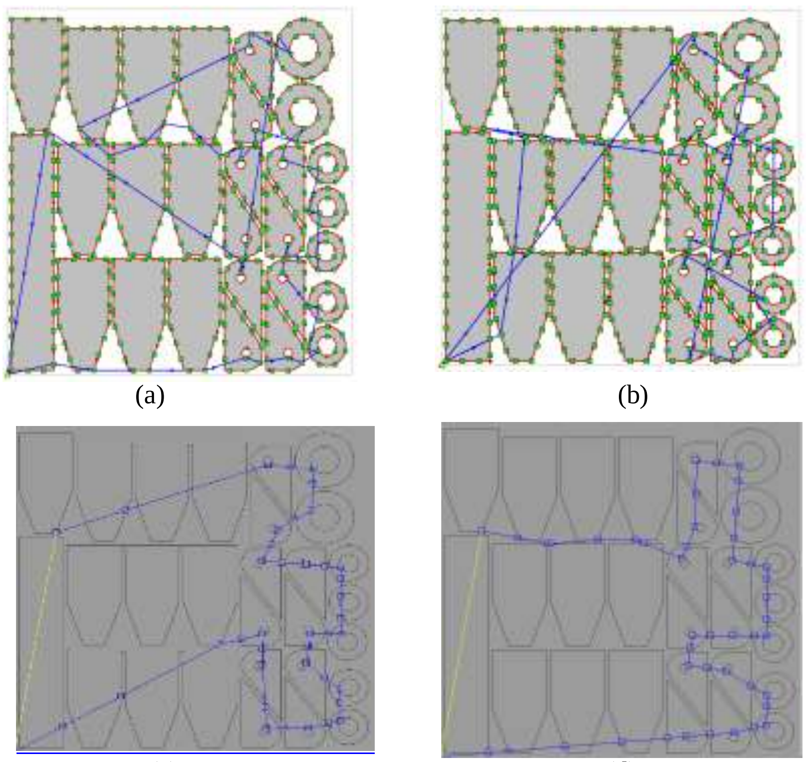
The following algorithms are used to solve each problem:

1. Relax_CCP (relaxation algorithm for finding insertion points [18] for the case of continuous base segments);
2. DP_GTSP (exact algorithm [19] based on a dynamic programming model for the case of discrete base segments and a problem of small dimension).

3. Greedy_GTSP (heuristic algorithm [20] for the case of discrete base segments and, if necessary, to minimize thermal deformations of the material when cutting parts on CNC machines. The algorithm is based on an iterative version of the greedy algorithm.

COMPUTATIONAL EXPERIMENT

As an illustration, consider the GSCCP task shown in Figure 3.

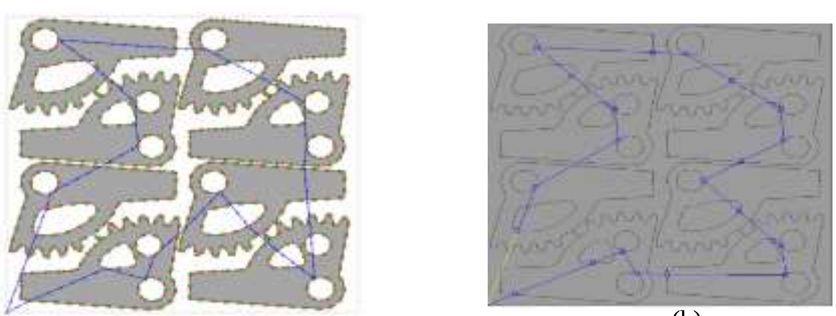


(a) (b) (c) (d)

Figure 4. An example of using the Greedy_GTSP (a, b) and Relax_CCP (c, d) algorithms for solution GSCCP

The minimum value of the objective function (2) for the given constants (C_{off}, C_{on}, C_{pt}) was provided by the Relax_CCP algorithm for a set of 39 basic segments (Fig. 4d) using a multi-contour cutting technique. For simplicity, all illustrations do not show insertion points, but only show the tool entry points into basic segments.

Another calculation result for another GSCCP task with two sets of basic segments (K_1 = 24, K_2 = 28) is shown in Fig. 5. Here, close values of the objective function showed the exact algorithm DP_GTSP (Fig. 5a) and Relax_CCP (Fig. 5 b).



(a) (b)

Figure 5. An example of using the DP_GTSP (a) and Relax_CCP (b) algorithms for solution GSCCP

Due to the limited size of the article, a graphical description of the segments is not presented. Both examples are real production examples of cutting designed in the CAM system "Sirius", which is used in a number of Russian industrial enterprises. Currently, the developed algorithms are being integrated with this CAM-system.

To test the developed algorithms, a specialized library of tests was created, which is also a set of real production examples of solving the nesting problem

CONCLUSION

A new class of problems (GSCCP) for the Cutting Path problem is considered. On the basis of the concept "basic cut-off segment" introduced by the authors, a new approach is proposed that allows solving such problems using a set of continuous and discrete optimization algorithms focused on their class of the tool path problem for CNC sheet cutting machines. This increases the likelihood of finding the optimal solution. The authors have proposed various precise and heuristic algorithms that take into account the specifics of sheet cutting. The approach is illustrated by computational experiments. The development of the first specialized library of instances for testing the algorithms of the CPP solution is reported. The library is prepared for open access.

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