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PROCESS PLANNING FOR HIGH-SPEED COIL-FED LASER CUTTING WITH TWO LASER HEADS

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Abstract

Coil-fed laser cutting is widely used for mass production in various industries. Using metal coils instead of metal sheets can not only streamline the feeding of the stock material into the workspace of laser cutting machines but also allow enlarging the size of the coil fed to the laser cutting machine to a virtually unlimited dimension. Practically, this is achieved by implementing machine designs that can either cut extremely long parts or have multiple laser cutting heads operating simultaneously. In the case of machine designs, in which laser heads operate on the full width of the coil, one laser head is positioned after another. It can, therefore, cut away material beforehand. This creates significant challenges for proper process planning. Cutting patterns must be laid out on the moving coil such that there is enough time for the laser heads to process part contours while they pass through the workspaces of the laser heads.

In this paper, a high-speed, high-dynamic laser cutting machine with two laser heads is considered. The workflow presented in this paper automates and integrates the process planning steps—from nesting to balanced, dynamics-aware toolpath generation—into a single, optimized digital process planning toolchain, eliminating the need for manual partitioning and sequencing and enabling the optimization of the machine throughput.

Keywords:
Laser cutting, coil, process planning, digital toolchain, CAD/CAM

1 INTRODUCTION

Laser blanking technology is a method that enables the continuous manufacturing of parts by unwinding material from a coil and cutting it using one or more cutting heads while the coil moves at a constant speed. In the final stage, the parts are automatically collected, resulting in a continuous and autonomous process. However, the process planning for this production method remains a manual task with multiple time-consuming steps.

The workflow of the classical laser blanking process usually consists of several steps.

Firstly, a set of 2d contours is positioned within the sheet dimensions. There exist different algorithms to “nest”, or to “pack”, 2d shapes next to each other in order to achieve some goals [Hopper 2001]. Typically, the amount of scrap material is to be minimized.

Secondly, the sequence of cutting moves must be assigned. This is a generalized traveling salesman problem (GTSP), in which all 2d curves must be visited at least once. Additionally, there are two types of moves – cutting and air moves. According to [Hoeft 1997], toolpath problems can be classified into three problem classes, as in [Dewil 2014]:

- ***Continuous Cutting Problem***: Each contour is to be cut once. Engagement into contours can be at any point, but it must cut the entire contour before it travels to the next contour. Accordingly, the same point must be used for entry and departure from the contour.
- ***Endpoint Cutting Problem***: Entering and exiting of contours are only at some predefined points. However, contours can be cut in sections.
- ***Intermittent Cutting Problem***: This is the most general version of the problem in which no restrictions on the enter-exit points are applied.

As can be seen, the toolpaths are classified based on how entry-exit points and whether single contours are being cut in an interrupted way, i.e., having only one point that serves as both the entry and exit point. Therefore, sequencing algorithms do optimize toolpaths by computing these points to reach different objectives. For instance, [Dewil 2014] used a heuristic-based approach to solve a GTSP while minimizing a spanning tree connecting contour partitions. [Sherif 2014] used simulated annealing to minimize air moves while maximizing material utilization. [Junior 2023] used evolutionary algorithms to minimize air move time.

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However, the case of multi-cutter process planning is more complex. The sequence optimization becomes a multiple-traveling salesman problem (m-TSP), which has additional restrictions, such as the presence of multiple traveling agents [Bektas, 2006]. [Dewil 2016] provided a review of research papers on using m-TSP for multi-head processes in contour crafting [Zhang 2013] and water-jet cutting [Li 2014], which had a special two-nozzle design with only the middle section of the working space being reachable by both nozzles.

While commercial CAD/CAM software offers sophisticated solutions for nesting on static metal sheets and generating toolpaths for single-head cutters, the process planning for continuous coil-fed, multi-head systems remains a significant challenge. Typically, this would involve a disjointed, multi-step manual process: an operator would first perform a nesting operation, then manually partition the cutting tasks between the heads, and finally generate and sequence the toolpaths for each head. This manual workflow is not only time-consuming and prone to sub-optimal solutions. Still, it is also infeasible for a dynamic system where nesting, load balancing, and motion planning are deeply interconnected due to the constant coil movement. The workflow presented in this paper automates and integrates these steps—from nesting to balanced, dynamics-aware toolpath generation—into a single, optimized digital process chain, eliminating the need for manual partitioning and sequencing and enabling the optimization of the machine throughput.

This paper focuses on the development of a sequence planning algorithm for a laser cutting machine equipped with two laser heads located one after another above a moving coil and having separate working spaces. The coil moves with a constant speed, resulting in a situation where each point of the coil is exposed to the laser working space only for a limited time. This means that, if not properly planned, a laser head may not have enough time to cut the required contours when they pass the working space. The second laser head not only increases the performance of the laser blanking machine but also allows balancing the load between the first and second heads to increase the utilization rate of the machinery. Since the machine aims for high-speed cutting, it is crucial to consider the trajectory planning of the moving parts of the machine to reduce time losses due to limitations in machine dynamics. It is important to note that nesting is performed in the coil coordinate system, while the laser head motion planning must consider the coil velocity and adjust the toolpath to ensure the programmed motion relative to the moving coil is accurate.

The rest of the paper is organized as follows. Section 2 presents the methodological framework used to develop the sequence planning algorithms. The validation procedure is described in Section 3. The conclusions and future work are summarized in Section 4.

2 METHODOLOGY

This chapter details the methodological framework employed for the development of sequence planning algorithms tailored to dual-head laser blanking systems. The algorithms target efficient process planning and optimization for high-speed laser blanking operations enabled by new laser blanking machine designs.

2.1 The machine setup

The machine prototype considered in this study features a crossbeam architecture, as shown in Fig. 1. The core of the motion system comprises three Cartesian axes (X, Y, Z). The X and Y axes are driven by four individual motors, two per support beam, to achieve high accelerations and speeds in the horizontal plane. The vertical Z-axis incorporates a linear motor for comparable high acceleration. The system configuration features two laser blanking machines working in series over the same constantly moving coil.

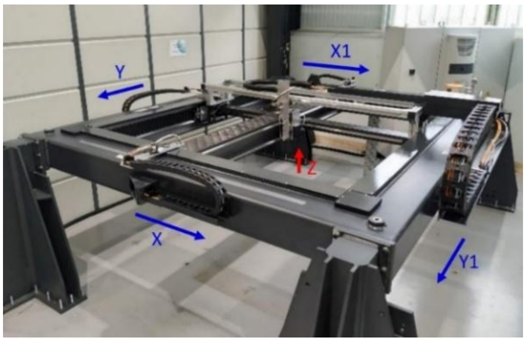

Fig. 1: Laser blanking machine prototype.

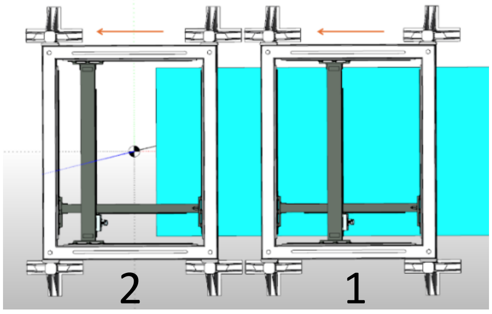

Fig. 2: Machine setup with two consecutive workspaces

Fig. 2 depicts the machine configuration with two workspaces. The coil passes through workspace one first. For this reason, the laser toolpath for the second machine is synchronized using the first machine as a reference. The laser toolpath in machine coordinates differs from the initial contour of the workpiece. This difference is caused by the constant motion of the coil, which displaces the x-coordinates of the points in the toolpath in the direction of motion of the coil. In Fig. 2, the motion of the coil is from right to left.

The transformation between the machine coordinate system and the coil coordinate system depends on the start point of the toolpath, cutting direction, coil speed, and the dynamics of the machine axes. The displacement of the toolpath points in the x direction is described by Eq. (1):

$$x_R = x_0 + \Delta t * s_c \quad (1)$$

Where x_R is the laser head position at cutting point x_0 from the initial contour, Δt is the time elapsed since the machine started cutting the contour, and s_c is the coil speed. It

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should be noted that the computation of the elapsed time Δt depends on the dynamic behaviour of the machine and is not trivial. For this reason, an accurate simulation of the machining process is required.

Changing the initial cutting point and the direction of cutting (clockwise or counterclockwise) changes the shape and the length of the toolpath, as depicted in Fig. 3.

a) Contour *b) Laser trajectory (counterclockwise)* *b) Laser trajectory (clockwise)*

Fig. 3: Initial contour and actual machine path with coil moving from right to left

2.2 Algorithmic implementation

This section describes the building blocks of the digital process planning tool.

Nesting

Before nesting (packing) of contours, contours need to be polygonised and converted into polygons since our implementation of nesting is based on Minkowski sum [Lam 2007, Nye 2000], which is a common approach for nesting with scrap minimization. Polygonization of the input contours is implemented to linearize the curves and distribute points to ensure that the resulting polyline remains within the tolerance from the initial curve.

Minkowski sum ensures that there is no overlap between polygons. The algorithm allows each polygon to be rotated in position with a fixed incremental angle of PI/8, as shown in Fig. 4.

The parameters used to configure the nesting modules are the following:

Type of contact: One important consideration when automatically placing workpieces on the coil is whether neighbouring workpieces are allowed to be in contact with each other and share common edges. Depending on process and requirement constraints, some workpieces may have to be placed at a certain distance from one another. If this is the case, the nesting algorithm works with offset curves that ensure the minimum required distance is kept during the placement of the parts.

Part rotations: it is possible to define if parts may be mirrored and rotated during the nesting process, and to select a limited number of rotations if needed.

Coil edge: It is possible to specify the minimum distance from the coil edge at which pieces can be placed. If the distance is zero, the pieces may be placed in such a way that straight workpiece segments coincide with the coil edge, resulting in a reduction of the total cutting length required to produce the pieces.

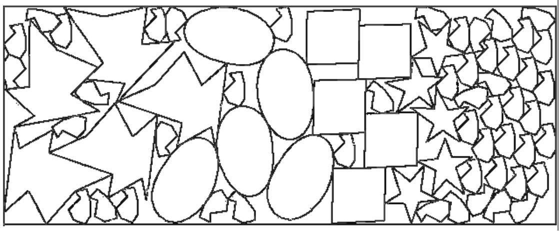

Fig. 4: Result of the nesting algorithm.

Weighting cut segments

Since the application is relevant to a highly dynamic process, the feed rate of lasers is expected to vary. The laser may decelerate at corners, especially at sharp ones. The idea is to provide a metric that could reflect the influence of varying feed rate along the path. Therefore, each linear segment has a weight value *W* assigned. The weight value is a function of the maximal angle with two adjacent line segments, as in Eq. (2). Parameter T, showing the degree of the direction change, in Eq. (3), is used to penalize direction changes, as in Eq. (4).

$$\alpha = \max(angle(segment_{i-1}, segment_i), angle(segment_i, segment_{i+1})) \quad (2)$$

$$T = 1 - \alpha/\pi \quad (3)$$

$$W = (1 - T) * Feed_{min} + T * Feed_{max} \quad (4)$$

Where $Feed_{min}$ and $Feed_{max}$ are defined as the bandwidth for the minimal and maximal speed of the laser.

Connecting (linking) polygons

Pairs of consequent polygons are linked by the shortest distance path. This step allows generating some of the entry-exit points. These points are also used as “split” points, points at which contours can be segmented into pieces to be cut by different lasers, i.e., one contour can be cut by different lasers. If contours touch at a point or line, the connecting link segment has a zero length.

Objective

While searching for the distribution of load between laser heads, each polygon segment is considered to have two possible directions of cutting, so-called clockwise and counterclockwise directions. Fig. 5 illustrates an example of how a set of contours can be sequenced between two lasers. In this example, the start points for both lasers are at the top of contour 0, whereas each laser follows the contours in the opposite direction. Therefore, the algorithm alternates between lasers and the direction of cut by inverting it to find smoother paths. Basically, with the given line segment weights *W*, the algorithm collects segments of polygons to assign them to each head such that there will be an equal mixture of “fast” (high W) and “slow” (low W) segments, while maximizing the total *W*. Different configurations might lead to almost identical total W. In such cases, a toolpath simulation is required to select an optimal strategy.

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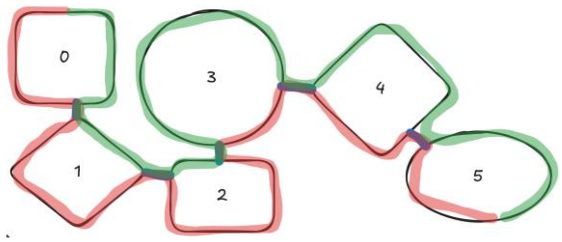

Fig. 5: Paths for laser heads (red and green parts are attributed to different laser heads).

Multiple start-end points

It has been recognized that placing start and end points may have a substantial impact on performance. The search for an optimal start-end pair of points is based on grid search, in which the first contours and two end contours are spawned with a fixed number of equally spaced points, as shown in Fig. 6. All possible combinations of start-end points are evaluated. The best one, in terms of load balance, is selected.

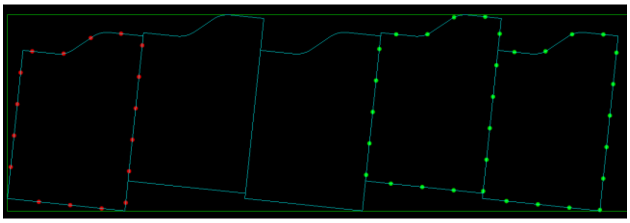

Fig. 6: Potential start points (red) and end points (green).

Inverting the direction of contours

As a contour can be traversed in both directions, both directions are incorporated into the search routine. When switching from one polygon to another, a laser head has an option to move in either direction. Often, it is beneficial to invert contour directions for each subsequent contour. This tends to result in smoother paths since the connection between contours becomes more tangential, as shown in Fig. 7.

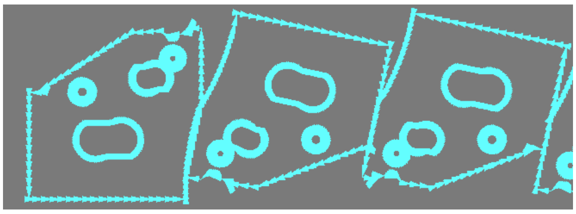

Fig. 7: Inverted contour directions after each next contour (contour directions are shown with arrows).

Corner smoothing

Since sharp corners in the toolpath appear to be bottlenecks due to the necessary slowdown, changing corner paths within a tolerance may result in better performance. Such sharp corners can be replaced by a polyline that is a linearized spline. The challenge is to find a balance between accuracy and performance without exceeding tolerance limits.

Splitting the task between laser heads

Fig. 8 shows how a set of relatively simple contours can be machined with two continuous laser paths, which are balanced in terms of estimated machined time.

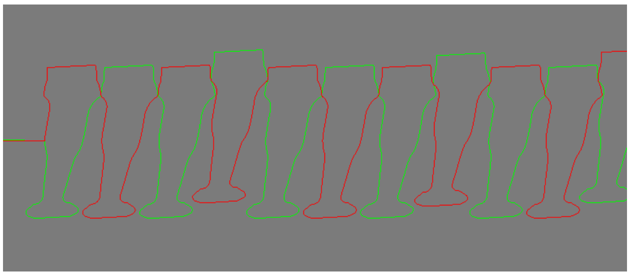

Fig. 8: Nesting of a simple contour, toolpath for laser head 1 (green), and toolpath for 2 (red).

The sequence planning is performed in the coil coordinate system, which is moving along with the coil itself. The laser heads operate in the machine coordinate system, though. Fig. 9 depicts trajectories of laser heads for the example mentioned above.

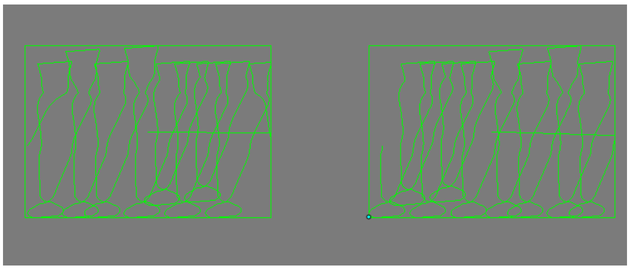

Fig. 9: Trajectories of laser head 1 (right) and laser head 2 (left)

Ideally, toolpaths must be continuous without air moves. If there is a substantial imbalance between laser head loads, one head may have insufficient time to complete its job. Therefore, the coil speed needs to be reduced, and the whole performance will decrease. The maximal coil speed can be used as the cost function to indicate the cutting performance.

3 VALIDATION

The developed algorithm was tested with a test sample with different optimization options enabled. These optimization options are explained in subchapter 2.2. Several geometric layouts of the nesting results are shown in Fig. 10-12. The results are presented in Table 1.

The toolpath is first simulated in a purely kinematic manner. Using a constant motion of the coil and the machine axes. Then, the toolpath simulation is adjusted using weights that depend on the local curvature of the polyline. In this step, the toolpath for both machines is synchronized to ensure the correct shape of the workpieces is achieved in the coil coordinate system. In a further step, the toolpath can be verified using the digital twin.

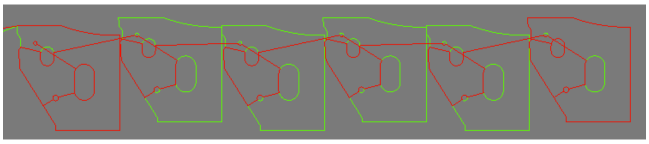

Fig. 10: Benchmark sample - nesting without rotation

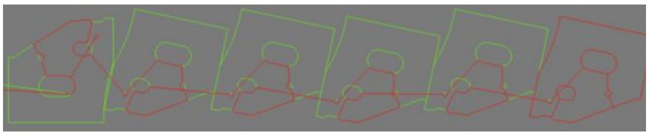

Fig. 11: Benchmark sample – nesting with rotation

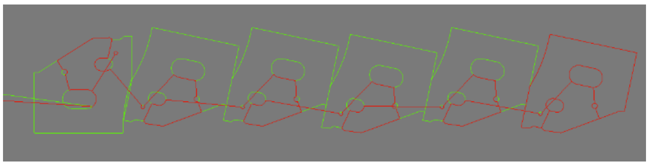

Fig. 12: Benchmark sample – multiple start-end points

Tab. 1: Comparison of metrics for different toolpath generation strategies.

Strategy	Relative machining time estimate
Nesting without rotation	100%
Nesting with rotation (NR)	55%
Multiple start-end points (MP) +(NR)	44%
Inverted contours (IC) + (MP) + (NR)	39%
Corner smoothing + (IC) + (MP) + (NR)	37%

4 CONCLUSIONS AND FURTHER WORK

In this paper, a process planning workflow for a laser sheet cutting process with a moving coil and two laser heads is presented. The workflow includes the following steps of the digital process chain: nesting (placing) the contours of the desired workpiece on the coil, taking those contours and splitting them up to distribute the workload between the two laser heads, creating a toolpath for the latter, and simulating this toolpath. A challenge here is to move from the nesting to the work partitioning and movement of the lasers, because of a transformation from the coil coordinate system to the laser head coordinate system is needed, and this transformation is dependent on the dynamic characteristics of the machine. The fully automated workflow so far is optimized towards reducing the process time.

For future work, the following aspects need to be tackled:

Currently, the work partition is optimized towards reducing process time. Here, other metrics like reduction of toolpath length or machine-dependent values need to be investigated and compared with each other. The integration of a realistic simulation model for the machine dynamics by using a virtual NC kernel (VNCK) would improve the reliability of the automated workflow. To demonstrate the increase in performance by using two laser heads, experiments using one laser head versus using two laser heads need to be conducted. Finally, real-scale cutting trials will be conducted to evaluate the process planning workflow.

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