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Time-optimized hole sequence planning for 5-axis on-the-fly laser drilling

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ABSTRACT

On-the-fly laser drilling requires the use of acceleration continuous trajectories, which are typically planned using time parameterized spline functions. In this operation, the choice of hole drilling sequence, and positioning timings in between the holes, play a critical role in determining the achievable cycle time. This paper presents a new algorithm for sequencing 5-axis on-the-fly laser drilling hole locations and timings. The algorithm considers machine tool and process constraints, as well as the temporal nature of the final commanded spline trajectory. The achievable productivity and motion smoothness improvement are demonstrated in the production of a gas turbine combustion chamber panel.

1. Introduction

On-the-fly laser drilling offers several advantages over percussion drilling. In percussion drilling, a series of shots are fired to completely open each hole while the part is stationary, followed by repositioning to the next hole. During on-the-fly drilling, the part is in continuous motion while the laser fires only one shot at a time at each hole, and the smooth positioning trajectory repeats itself until all holes are opened. This results in:

1. Better material properties and feature quality, due to reduced thermal loading.
2. Smoother axis motion, when a spline trajectory is used [1], which reduces vibrations induced onto the laser optics.
3. Less downtime for optics realignment, achieved through vibration reduction.
4. Increased productivity, as improved motion smoothness can be translated into higher drilling speeds by quickening the process while keeping the vibration levels limited.

Our earlier work had focused on time-optimal trajectory generation for 5-axis on-the-fly laser drilling [2]. The machine configuration, a typical hole pattern with varying orientations, and the hole elongation phenomenon intrinsic to the process are shown in Fig. 1. The hole sequence was determined using the 'Nearest Neighbor' (NN) algorithm in part coordinates [3], in which the hole closest to the current one is chosen as the next waypoint, and if the distance exceeds a threshold a new sequence is initiated. In continuing investigation, it was determined that:

1. The sequence in which the holes are ordered has a profound impact on the actuator trajectories, and hence the cycle time.
2. The acceleration effects in the final trajectory, which are not considered in the NN approach, also need to be taken into account in sequence planning, for improved productivity.

While the hole sequencing task resembles the Traveling Salesman Problem (TSP) known from combinatorial mathematics [4] (where a minimum-cost, e.g. distance, connection needs to be found that passes through all given waypoints only once), there are aspects of on-the-fly laser drilling that make the problem different and even more challenging than TSP, as well as earlier research in hole sequencing for stationary laser drilling [5]:

1. Since the final trajectory will be a spline that smoothly connects the sequenced waypoints, the travel durations in between the holes (which strongly influence the spline parameterization) have to be carefully selected. *Hence the sequencing algorithm has to solve for both the order of the waypoints and also the timings in between.*

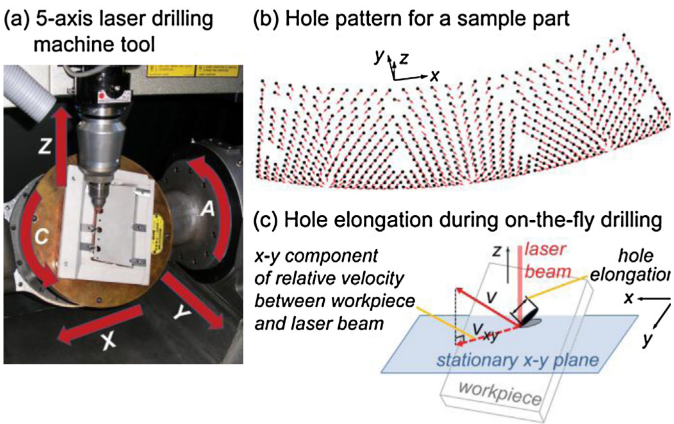

Fig. 1. Laser drilling machine, sample pattern, and hole elongation [2].

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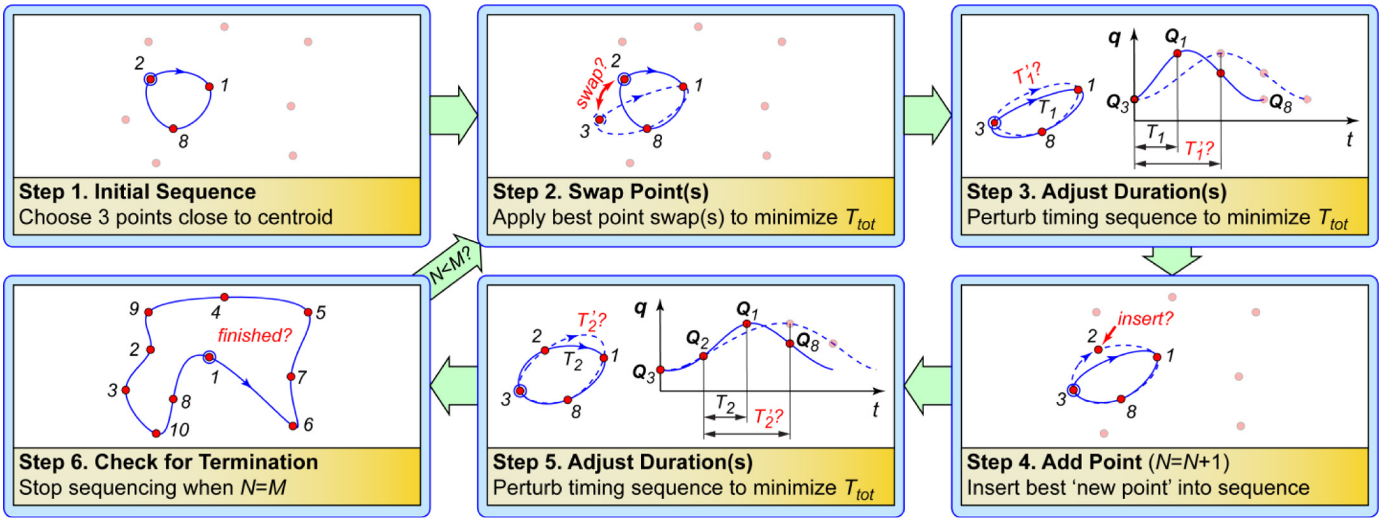

Fig. 2. Proposed waypoint and duration sequencing algorithm.

2. The objective is to minimize the drilling cycle time while adhering to machine tool and process constraints. *Therefore, the temporal nature of the final spline trajectory needs to be considered, along with the machine kinematics and limits.*

For a part with only M (=10) holes and k (=5) possible timing levels, there can be $M! \times k^M$ ($\sim 3.54 \times 10^{13}$) trajectory sequences. In gas turbine combustion chamber panels, the number of holes may vary between hundreds and thousands. Therefore, the need for an efficient and effective sequencing method has been the motivation behind the heuristic algorithm presented henceforth in this paper.

2. Proposed solution

The proposed algorithm, and data structure used in candidate sequence evaluation, are illustrated in Figs. 2 and 3. Inputs to the algorithm are hole locations $\boldsymbol{Q}_k$ ($k = 1, \ldots, M$) defined in joint (actuator) coordinates $\boldsymbol{q} = [x\ \ y\ \ z\ \ a\ \ c]^{\mathrm{T}}$ (Fig. 1a). For clear presentation of the algorithm, candidate evaluation is explained first in Section 2.1, followed by the sequencing steps in Section 2.2. The implementation is described in sufficient detail to enable replication. Lengthy equations, however, are avoided for brevity.

2.1. Candidate sequence evaluation

Considering Fig. 3, for a candidate sequence with N elements, the optimization variables are the order of the waypoints ($\boldsymbol{S}$) and

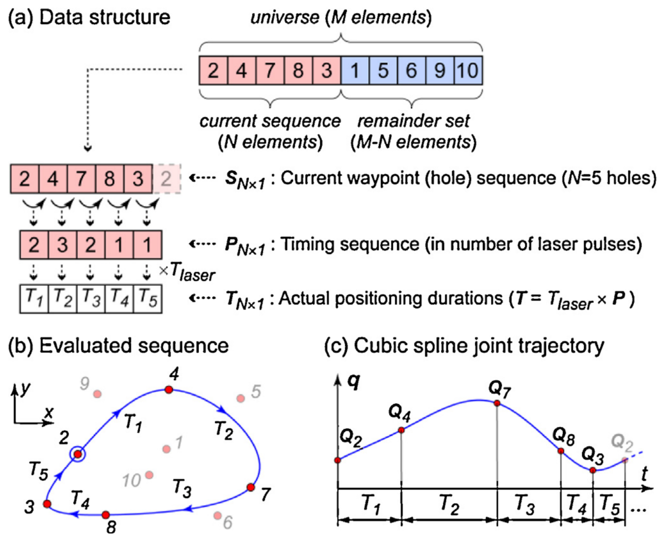

Fig. 3. Data structure and candidate sequence evaluation.

timings in between ($\boldsymbol{P}$) (measured in number of laser pulses). Since on-the-fly drilling needs the positioning trajectory to repeat itself, preferably without coming to a full stop, the closed cubic spline has been the natural choice for the basis curve. It is acceleration continuous (i.e., jerk limited) and very efficient solve.

The closed cubic trajectory is computed by setting up a system of N linear equations, in which the unknowns are actuator velocities ($\boldsymbol{V}_j$) at hole locations (i.e., $\boldsymbol{L}(\boldsymbol{T})\cdot\boldsymbol{V}_j = \boldsymbol{\xi}_j, j = x, y, z, a, c$). Since, $\boldsymbol{L}(\boldsymbol{T})$ is block diagonal and common to all axes, the calculations are accelerated by re-using its inverse to solve the command profiles for all of the axes. The cubic has piecewise constant jerk, linear acceleration, and parabolic velocity in each segment, thus allowing the peak jerk, acceleration, and velocity values to be evaluated analytically without requiring interpolation. The velocity component v_{xy} at the drilling location (Fig. 1c), which influences hole elongation, is also calculated from the spline coefficients and by considering the machine tool kinematics [6].

During each sequence evaluation, the cubic spline is first constructed assuming a unit laser pulsing period ($T_{\mathrm{laser}} = 1$ s) in computing the initial segment durations ($\boldsymbol{T} = T_{\mathrm{laser}} \times \boldsymbol{P}$). Afterwards, time scaling is applied to the whole trajectory by updating the laser pulsing period to T'_{laser}, such that:

1. All of the profiles for actuator velocity, acceleration, and jerk are within their designated limits. Also, v_{xy} is limited at drilling instances. The smallest possible time scaling factor $\alpha_{\min}$, which ensures that all of the kinematic profiles are within their bounds, and that at least one of them reaches its limit, can be determined by considering that time scaling by α leads to velocity, acceleration, and jerk scaling by α^{-1}, α^{-2} and α^{-3}, respectively. This calculation is shown in detail in [2]. Then T'_{laser} is chosen as $T'_{\mathrm{laser}} \geq \alpha_{\min}$.
2. T'_{laser} has to be above a certain minimum duration $T_{\min}$ ($\cong$27 ms) required for the quick shutter in the optics path to engage and disengage. The quick shutter serves to divert the laser away from the workpiece when the positioning duration is longer than a single laser pulsing period.
3. $1/T'_{\mathrm{laser}}$ has to be an integer frequency in Hertz. This is a programming requirement for the laser control electronics.

After these adjustments, the final segment durations are computed as ($\boldsymbol{T} = T'_{\mathrm{laser}} \times \boldsymbol{P}$) and the time scaling is applied to the earlier fit spline, by multiplying the third, second, and first degree coefficients by $(1/T'_{\mathrm{laser}})^3$, $(1/T'_{\mathrm{laser}})^2$, and $(1/T'_{\mathrm{laser}})$, respectively. This avoids the need to re-solve the cubic trajectory.

The objective function in evaluating a candidate sequence is defined as the time required to complete one full pass of the on-the-fly drilling trajectory: $T_{\mathrm{tot}} = T_1 + T_2 + \cdots + T_N$. Minimizing this duration enables the minimization of the part cycle time.

Here, the drive velocity, acceleration, and jerk limits are considered, as they can be conveniently determined from the CNC.