Task Sequencing for Remote Laser Welding in the Automotive Industry

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Abstract

This paper proposes a new model and algorithm for task sequencing in remote laser welding in the automotive industry. It is shown that task sequencing (in which order to weld the seams) is strongly related to path planning (how the welding robot should move), therefore the two problems must be solved together, in an integrated way. The problem is modeled as a direct product of a traveling salesman and a path planning problem, and a tabu search algorithm is proposed for solving it. Computational experiments show that the proposed method leads to a substantial reduction in the cycle time of the welding operation compared to an earlier approach.

Introduction

One of the most significant current technological trends in car body making is the spreading application of remote laser welding (RLW). This contactless technology eliminates the most important bottleneck of earlier joining techniques, the accessibility issues between the welding gun and the workpiece, by welding from a distant point using a laser beam. This results in up to 80% lower cycle times, reduced operating costs, and higher freedom in part design (Park and Choi 2010). Nevertheless, the successful application of RLW also requires the elaboration of novel methods for process planning that are able to capture all important features of the new technology. In this paper, we address one of the most important optimization problems related to process planning for RLW, task sequencing.

The RLW technology, including the typical design of an RLW cell and current limitations, is presented in (Tsoukantas et al. 2007). Applications of RLW in the automotive industry are reviewed in (Shibata 2008). The importance of automated process planning for RLW is emphasized in (Hatwig, Reinhart, and Zaeh 2010). Algorithms for task sequencing and robot path planning are introduced in (Reinhart, Munzert, and Vogl 2008). Task sequencing is performed by solving a traveling salesman problem (TSP) over the positions of the seams to be welded. A drawback of the approach is that it considers merely seam positions in the Cartesian space, and ignores all accessibility considerations and technological parameters. A similar problem, the minimization of processing time in a milling operation, is investigated in (Castelino, D'Souza, and Wright 2002). A generalized TSP approach is proposed, where the nodes correspond to the candidate tool entry/exit points for machining a feature. The same problem is investigated in the context of resistance spot welding (RSW) by (Saha et al. 2006), who exploit that the RSW robot must move between discrete positions, each corresponding to a candidate robot configuration for welding a spot. However, this approach is not directly applicable for RLW, since here the robot must move along a continuous trajectory, whose candidate corner points and the path segments between them cannot be generated efficiently a priori.

Technological Background

The Welding Process

The recent development of a new generation of laser sources, such as fiber lasers, enabled laser welding with an operating distance (focal length) above one meter. The new technology, RLW, joins sheet metal parts without physical contact or even a close approach. This, on the one hand, ensures extremely fast positioning speed compared to classical RSW, where a vast welding gun must contact the workpiece. The high productivity of the technology results in up to 80% lower cycle times and reduced operating costs, making RLW economically profitable despite the high initial investments. In addition to the direct economic gain, the abolishment of the accessibility issues removes many earlier constraints on part designs, an advantage that can be turned easily into parts with reduced weight, yet higher stiffness. This, in the automotive industry, facilitates the design of lighter and more efficient cars, without compromising safety.

An RLW operation consists in joining two or more sheet metal parts at various joints. In this paper, we assume stitch welds, i.e., linear welding seams with a typical length of 15-30 mm each. During the operation, the parts are held in a fixture, which is either stationary or attached to a rotating table. It is assumed that the operation is performed by a single RLW robot. A typical RLW robot consists of a robot arm with 4 rotational joints and a laser scanner. The robot arm moves the scanner with a maximum speed of 0.2-0.5 m/s, and due to the low scanner weight, with a rather high accel-

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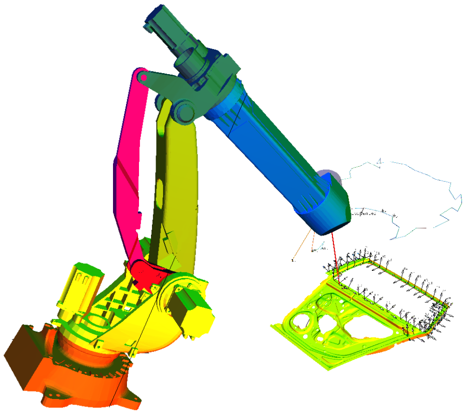

Figure 1: RLW robot welding a car front door.

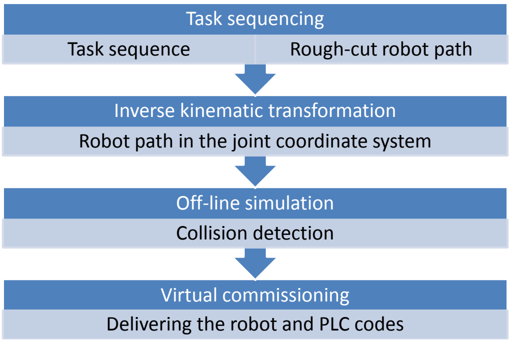

Figure 2: Workflow in the off-line programming system. The paper focuses on the first step, task sequencing integrated with rough-cut path planning.

eration. The scanner contains a laser source, two mirrors for the rapid positioning of the laser beam (up to 5 m/s), and a focus lens to regulate the focal length. Hence, the typical RLW robot is a redundant kinematic system with 7 degrees of freedom, in which the mirrors of the scanner move an order of magnitude faster than the mechanical joints of the robot arm. A typical RLW robot is depicted in Figure 1.

The robot can weld a seam if the scanner is located within the *focus range* (e.g., 800-1200 mm) from the seam, and the *inclination angle* (i.e., the angle between the laser beam and the surface normal) is not more than a specified technological parameter (e.g., $15°$). These constraints define a truncated cone above the seam, which will be called the *access volume* of the seam. Since the length of a stitch is significantly smaller than other characteristic dimensions in the welding process, it is reasonable to assume that all points of the stitch can be processed from a single, conical access volume. Each seam can be welded at a given speed (e.g., 50 mm/s), which depends on the thickness and the material of the parts to join. Each stitch must be processed without interruption. The robot can weld the seam while in motion, therefore the trajectory of the scanner must be a curve in the 3D space, such that sufficient time is spent in the access volume of each seam. There are 30-60 stitches to weld in an RLW operation in the automotive industry.

Certainly, the RLW technology has its limitations, among which perhaps the most important is that it cannot weld through thick metal sheets. As a result, only certain subassemblies of the car body, e.g., doors and roofs, are welded using RLW, while other parts of the body are still assembled using traditional RSW.

An Off-line Robot Programming Approach

In industrial practice, robot programming is still mostly performed by on-line programming, i.e., by manually guiding the robot from one position to the next, at very small steps, which is a rather time consuming approach. Our goal is to implement a complete off-line programming toolbox for RLW, which can provide an automated method for computing close-to-optimal robot programs. This involves the optimization of the task sequence (i.e., processing sequence of the individual seams); robot path planning; the inverse kinematic transformation that converts the path from the workpiece coordinate system to the joint coordinate system of the robot; and the simulation of the robot path, including collision detection. Finally, the robot and PLC programs are generated in an automated way. This paper focuses on the first step of the procedure, as displayed in Figure 2.

We show that the problems of welding task sequencing and rough-cut path planning are strongly related, and therefore must be solved together, in an integrated way: classical path planning requires the task sequence to be included in its input, but it is not possible to measure the quality of a task sequence without a corresponding robot path. On the other hand, due to the computational complexity of performing geometric calculations in the robot joint coordinate system (Kucuk and Bingul 2006), we propose planning the robot path first in the Cartesian space, and converting it to the robot's joint space only afterwards, by performing the inverse kinematic transformation.

Problem Definition

The investigated problem consists in sequencing the individual welding tasks and computing a rough-cut robot path, in such a way that the cycle time of the complete welding operation is minimized. It is assumed that there is a set of n welding tasks, denoted by $\{s_1, s_2, ..., s_n\}$, to be performed by a single robot in a single operation, and each task corresponds to preparing a single seam. Each seam is characterized by its access volume, C_i, i.e., a truncated cone in which the scanner must be located while processing the seam, and the associated welding time, t_i. It is assumed that the maximum robot speed (speed of the scanner), v, is independent of the position in the working area. Then, the problem consists in determining the optimal task sequence, $(p_1, p_2, ..., p_n)$, where $p_i = j$ means that seam s_j is at the ith position in the task sequence, and the corresponding scanner path.

It is easy to observe that the optimal scanner path for a given sequence is a broken line defined by the $2n$ points $(a_1, b_1, a_2, b_2, ..., a_n, b_n)$, where a_i is the position of the scanner when it starts welding seam s_{p_i}, the so-called *entry point*, and b_i is the scanner position when it completes welding s_{p_i}, the *exit point*. Obviously, $a_i, b_i \in C_{p_i}$ is a constraint. Paths with $b_i = a_{i+1}$ are allowed, moreover, this situation reflects an efficient solution in which robot motion and welding overlap completely in that section of the solution. The time of robot motion between points b_i and a_{i+1} is $\frac{d(b_i, a_{i+1})}{v}$, while motion between a_i and b_i takes $\max(t_i, \frac{d(a_i, b_i)}{v})$ time, i.e., the maximum of the necessary robot motion time and the welding time. It can be observed that there exists an optimal path where $d(a_i, b_i) \leq t_i v$, and motion between each pair a_i and b_i takes exactly t_i time. In the sequel, we will restrict our search to such kind of paths. It is assumed that the robot has an infinite working area, and collision checking does not have to be performed at the time of task sequencing, and hence, there are no further constraints that bound the choice of a_i and b_i. Finally, the objective is minimizing the cycle time, i.e., the total time of executing the task sequence along the selected scanner path.

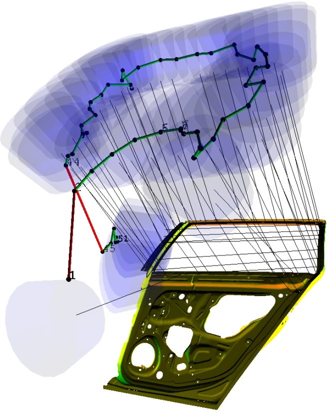

Figure 3: A solution of the task sequencing problem. The robot moves the laser scanner along the red path above the workpiece, and welds the seams from their access volumes, indicated by the blue truncated cones.

Solution Approach

The problem in scope can be considered as the direct product of a traveling salesman problem (TSP, for optimizing the task sequence) and a path planning problem in the 3D space (for finding the corresponding scanner path). For solving this problem, a tabu search algorithm has been developed. The algorithm combines adaptations of classical local search operators for TSP for modifying the task sequence, and a path planning heuristic that computes a close-to-optimal scanner path for each candidate task sequence. In each iteration, a next solution is selected according to the rules of the tabu search meta-heuristic. The algorithm terminates when it hits the defined time limit.

Tabu Search over Task Sequences

Initial solution The initial solution is constructed using an adapted version of the *farthest insertion* heuristic (Rosenkrantz, Stearns, and Lewis 1977). The algorithm starts with a partial tour consisting of two seams whose access volume mid-points are the farthest from each other. Then, in each iteration, for each seam, it looks for the best position for inserting the given seam into the partial tour, by calling the path planner algorithm for evaluating all possible insertion positions. The seam whose best insertion causes the greatest increase in the cycle time is selected, and it is inserted at its best position.

Neighborhood functions Due to the high complexity of evaluating a neighbor (the path planner algorithm must be run), we restricted ourselves to the application of small-size neighborhoods: the *2-opt* (deleting two edges and reconnecting the tour) and *or-opt* (relocating a segment of the tour of max. length k to another position, in forward or backward orientation) neighborhoods, with sizes $O(n^2)$ and $O(kn^2)$, respectively (Johnson and McGeoch 1997). Our neighborhood function consists in applying the above TSP operators to the task sequence, and then computing a new scanner path for the received task sequence.

Let us define a continuous-welding subsequence (CW-subsequence) as a section of the task sequence, $P_{ij} = (p_i, ..., p_j)$, such that $b_k = a_{k+1}$ for all $k = i, ..., j-1$, i.e., the robot can weld the corresponding seams without any idle time. Furthermore, let us define a CW-move as an application of any neighborhood function that affects only a single CW-subsequence P_{ij}, and leaves its head, p_i, and tail, p_j, unchanged. A peculiarity of our task sequencing problem is that CW-moves very often result in equivalent, in a sense symmetric solutions, and have negligible impact on the overall cycle time, only via potential modifications of a_i and b_j. Consequently, a tabu search with complete 2-opt and or-opt neighborhoods often circulates in a set of symmetric solutions until all CW-moves receive a tabu status, which is a lengthy and unproductive procedure.

In order to avoid this negative effect, CW-moves are removed from the neighborhoods during the tabu search. Nevertheless, after the termination of the tabu search, a fast hill climbing search is performed with the complete 2-opt and or-opt neighborhoods to realize the potential minor gains by CW-moves. This hill climbing search terminates quickly in a local optimum, within a couple of iterations.

Lower bounds for filtering the neighborhood In order to prune the neighborhood further, the following lower bound (LB) estimation is computed for each neighbor. A move reduces the cycle time by removing edges (p_i, p_{i+1}) from the task sequence, resulting in a decrease of $\frac{d(b_i, a_{i+1})}{v}$. At the same time, the move adds other edges, increasing the cycle time by at least the smallest distance of the two corresponding access volumes times v. The number of edges removed and added depends on the type of the move. If the LB on the increase of the cycle time is positive for a move, then that neighbor is neglected; otherwise, it is evaluated by the path planning algorithm.

Tabu list When performing a move, the undirected edges deleted from the tour are added to the tabu list, and a subsequent move will be declared tabu if it reinserts such an edge into the tour. The length of the tabu list is fixed to n, the number of seams, and the list is managed in a FIFO fashion. The aspiration condition is that the newly found solution is better than any previous solution.

Computing the Scanner Path

The path planner algorithm computes a close-to-optimal scanner path for a fixed task sequence, which is a candidate next solution in the tabu search. The incremental algorithm departs from the path computed for the current solution, and adapts it to the changes performed by the given neighborhood function (for the initial solution, the algorithm departs from a path where both a_i and b_i coincide with the mid-point of the cone C_{p_i}). The implemented algorithm sweeps along the broken line for a fixed number of iterations, and adjusts a single point of the broken line at a time.

During the adjustment of an entry point a_i, all other points of the broken line, including its predecessor, b_{i-1}, and successor, b_i, are assumed to be frozen. Then, the new position of a_i, denoted by a'_i, must satisfy the following conditions:

- a'_i must be in the access volume C_{p_i}, a truncated cone;
- according to the dominance condition $d(a'_i, b_i) \leq t_i v$, a'_i must be in a sphere centered at b_i, with radius $t_i v$. This sphere is denoted by S_i;
- the distance $d(b_{i-1}, a'_i)$ should be minimized.

This corresponds to the problem of finding a new point a'_i, closest to the fixed point b_{i-1}, inside a convex shape received as the intersection of a truncated cone and a sphere. Since there is no closed-form solution for this geometric problem, we apply the following heuristic:

- If b_{i-1} is inside C_{p_i} and S_i, then let $a'_i := b_{i-1}$, return;
- Let x be the closest point to b_{i-1} in the cone C_{p_i} (with $x = b_{i-1}$ if $b_{i-1} \in C_{p_i}$);
- Let a'_i be the closest point to x in the sphere S_i (with $a'_i = x$ if $x \in S_i$).

To observe the feasibility of the point a'_i computed in this way, note that it is inside S_i by construction. Furthermore, a'_i is inside C_{p_i}, too, since it is on the line segment between x and b_i, which are both inside the convex shape C_{p_i}. The geometric calculations are presented in detail in the extended, technical report version of this document (Kovács 2012). The adjustment of an exit point b_i works in an analogous way. The two end points of the broken line are determined according to the rule $a_1 := b_1$ and $b_n := a_n$.

Experimental Results

The proposed algorithm has been evaluated on problems involving the assembly of a car front door using RLW. Four variants of two car door designs have been considered, each involving ca. 50 welding seams. All process parameters were set to match a realistic industrial setting. Three algorithms have been compared: the proposed algorithm, which performs integrated task sequencing and path planning, denoted by TS-PP; the algorithm of (Reinhart, Munzert, and Vogl 2008), which solves a TSP over the seam positions and computes the robot path afterwards, RMV; and a modified version of RMV that solves the TSP over the mid-points of the access volumes, instead of the seam position, RMV*. The algorithms have been implemented in C++, and the latter two algorithms used ILOG CP as a TSP solver. A time limit of 60 seconds was applied.

	TS-PP		RMV		RMV*	
	cycle	idle	cycle	idle	cycle	idle
Part1	23.65	3.25	51.86	31.46	24.87	4.47
Part2	27.60	6.80	94.66	73.86	30.34	9.54
Part3	30.46	9.66	54.31	33.51	32.74	11.94
Part4	29.23	8.43	149.35	128.55	32.27	11.47
Avg.	27.74	7.04	87.55	66.85	30.06	9.36

Table 1: Computational results.

The results are summarized in Table 1, which displays the overall cycle time and the idle time (part of the cycle time when the laser beam is switched off) in seconds for each algorithm and each workpiece. The results show that TS-PP outperformed the other algorithms on all instances. In particular, it became obvious that a task sequence computed based solely on the seam positions is unsuitable for workpieces with complex geometry, since it leads to the scanner head moving in a zigzag above seams that have nearby positions but different surface normals. Consequently, RMV resulted in up to 5 times higher cycle times and up to 15 times higher idle times than TT-PS. RMV* performed significantly better than RMV, but still achieved 5-10% higher cycle time and 24-40% higher idle time than the proposed TS-PP algorithm. This gain can be regarded as the benefit of integrating task sequencing and path planning.

Conclusions

This paper proposed a new model and a tabu search algorithm for task sequencing for RLW in the automotive industry. It has been shown that a significant gain can be achieved by integrating task sequencing and rough-cut path planning. The proposed algorithm clearly outperformed the single earlier approach proposed for RLW task sequencing, as well as an improved version of that approach.

Our goal is to develop a complete off-line programming toolkit for RLW in the automotive industry. This toolbox is expected to help production engineers generate efficient robot programs from the description of the workpiece and the available resources in a reproducible way, much quicker than it is done manually today. In addition, automating this planning level supports the verification of decisions made on higher levels of the planning hierarchy, e.g., the configuration of the welding cell. The current model and algorithm constitute a first step towards these goals. Future research will focus on the detailed evaluation of the proposed algorithms, as well as automated techniques for collision avoidance, which is a serious issue for workpieces that have a significantly more complex geometry than the car doors considered above, e.g., a car body-in-white.

Acknowledgements

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