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## Efficient sequencing of industrial robots through optimal control

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### Abstract

In a production plant for complex assembled products there could be up to several hundred robots used for handling and joining operations. Thus, improvements in robot motion can have a huge impact on equipment utilization and energy consumption. By combining recent algorithms for collision free numerical optimal control and for optimal sequencing, we are able to cut down on energy consumption without sacrificing cycle time. The algorithm has been successfully applied to several industrial cases demonstrating that the proposed method can be used effectively in practical applications to find fast and energy efficient solutions.

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### 1. Introduction

By using Computer Aided Engineering (CAE), physical prototypes can be replaced by simulation, new products can be introduced faster, the efficiency of the production system can be optimized using mathematical methods and algorithms, and it can be done by simulation experts and production engineers in a safe and healthy environment.

The automotive industry is an example of an equipment and energy intensive manufacturing, where up to 28% of the vehicle life cycle energy is spent during production ([1]). For example, a typical automotive car body consists of about 300 sheet metal parts, joined by about 4000 welds. Typical joining methods are spot welding, arc welding, gluing and stud welding. In car body assembly plants, the welds are distributed to several hundred industrial welding robots, which are orga-

nized in up to 100 stations. The body shop is indeed investment intense, with the robots as the main consumer of energy ([1]). In [2] it is highlighted how utilization affects different aspects of sustainable production, the link between utilization and productivity, as well as practical considerations when improving utilization in manufacturing industry. Therefore from a sustainability perspective it is highly motivated to develop new software methods and algorithms for further improvement of equipment utilization and energy efficiency of robotized manufacturing systems.

In [3] it is shown that the balancing of weld work load between the executing stations and robots has a significant influence on achievable production rate and equipment utilization. Robot line balancing is a complex problem, where a number of welding robots in a number of stations are available to execute an overall weld load. Each weld is to be assigned to a specific station and robot, such that the line cycle time is minimized. Line balancing efficiency depends on station load balancing, robot welding sequencing, path planning and

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effectiveness of robot coordination for collision free execution within each other's working envelopes. Robot coordination impairs cycle time by inserting waiting positions and signals into the original paths. At Volvo Cars it has been proven that by using automatic path planning and line balancing instead of standard off-line programming the cycle time in welding lines can be improved by as much as 25%. The next step for improving the automatic path planning and line balancing is to include detailed optimization of motion profiles between welds. This choice is also from an energy efficiency aspect motivated. Meike and Ribickis [1] investigated different strategies to operate robots in an energy efficient way. Motion profile optimization was one of the strategies pointed out among others such as automatic shut-down and start-up, reusing braking energy, and brake management.

Global methods for optimal control are in general only applicable to systems of relatively few degrees of freedom or to problems with a special structure, see [4] for an example of such a problem. Most often one has to resort to local methods in order to handle more general problems. That is the path taken in this work where we will be using a direct transcription method called Discrete Mechanics and Optimal Control (DMOC), please refer to [5] for details on direct transcription methods in general and [6] for the DMOC method in particular. Direct transcription methods have been applied to solve optimal control problems for industrial robots before, for example by [7]. In this paper we combine recent advances in sequencing and collision free optimal control of industrial robots to create an efficient algorithm for automatic robotic path planning. In order to compute the travel cost between two locations our algorithm first uses a path planner to create an initial collision free path between the locations. The path is then refined using local numerical optimal control techniques to minimize our cost function. This minimum travel cost between nodes and the cost of visiting the nodes are then used by the sequencer in order to find the best possible sequence to complete the entire operation. Collision avoidance is incorporated into the optimal control problem, in the same way as in [8], by approximating the geometry in configuration space rather than  $\mathbb{R}^3$  making the size of the resulting optimization problem independent of the complexity of the geometry which contrasts most existing methods, for example [9] and [10].

## 2. Method

Here we describe the main steps of our algorithm. The sequencing problem is described in 2.1. In sec-

tion 2.2 we describe how to formulate the optimal control problem associated with the costs used by the sequencer, section 2.3 shows how to discretize and solve this problem, and in section 2.4 we provide details on how to incorporate collision avoidance in the optimal control problem.

### 2.1. Sequencing

In automotive applications, robots are usually assigned a number  $M$  of tasks, consisting of welding and sealing operations, for example. Each task can be done in several ways, and they can be performed in different orders. Thus, minimizing the cycle time requires choosing a robot configuration for each task and deciding the order in which the robot performs the tasks. The problem can be modeled as a Generalized Traveling Salesman Problem (GTSP), which, in this work, is solved exactly for instances up to  $M = 20$ , and by efficient heuristics for larger problems. The exact algorithm is a straightforward generalization of the dynamic programming approach described in [11] for solving the TSP. When this approach is not suitable, an algorithm based on metaheuristics and local search techniques is used: tour improving operations include 3-opt exchanges, double bridge and others, see [12].

Moreover, it is necessary to find collision-free paths between the chosen configurations for consecutive tasks. This is the most expensive part from the computational point of view, therefore a lazy approach is adopted in order to minimize the number of path planning queries needed. The overall method starts by computing a lower bound for all the robot paths. Thereafter, it iteratively finds a minimum cost sequence of tasks, computes collision free motions, and updates the costs of these paths. The algorithm terminates when the time limit is reached or when the required optimality gap is achieved. This approach is very efficient and can be naturally extended in order to deal with other measures of optimality, as the ones considering energy and robot dynamics. However, a crucial issue for good performance is the tightness of the lower bounds. When the function to be minimized is the time, good lower bounds are easy to compute, for example by considering the maximum speed of the joints and paths computed by linear interpolation in the robot configuration space. In this work, anyway, extensions to minimum energy bounds are not straightforward, therefore we approximate the paths costs by providing estimations that take into account static energy consumptions at the start and end configurations for a given path. These costs are not necessarily strict lower bounds but lead to high convergence rate and good overall quality.

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