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Research paper

Optimization of the robot and positioner motion in a redundant fiber placement workcell

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ABSTRACT

The paper proposes a new methodology to optimize the robot and positioner motions in redundant robotic system for the fiber placement process. It allows user to find time-optimal smooth profiles for the joint variables while taking into account full capacities of the robotic system expressed by the maximum actuated joint velocities and accelerations. In contrast to the previous works, the proposed methodology possesses high computational efficiency and also takes into account the collision constraints. The developed technique is based on conversion of the original continuous problem into a discrete one, where all possible motions of the robot and the positioner are represented as a directed multi-layer graph and the desired time-optimal motions are generated using the dynamic programming that is applied sequentially for the rough and fine search spaces. To adjust the optimization results to the engineering requirements, the obtained trajectories are smoothed using the spline approximation. The advantages of the proposed methodology are confirmed by an application example that deals with a planar fiber placement robotic system.

1. Introduction

Currently, composite materials are increasingly used in industry [1,2]. Compared to traditional ones, they have good strength-to-weight ratio, durability, flexibility of shaping and corrosion resistance [3,4]. Accordingly, they are extremely attractive for fabrication of large dimensional parts in aerospace, automotive and marine industries. The conventional way of manufacturing composite based components is labor intensive tape laying procedure. This manual process is quite slow and expensive, with low repeatability [3]. For efficient fabrication of composite parts, automated tape laying (ATL) is a more productive method. This is a specific technique which drives a technological tool laying a continuous composite tape onto molds automatically. However, ATL has a drawback that it is limited by the mold shapes. For a mold surface with high variation curvatures, tape wrinkling and overlap appear, and it decreases the mechanical performance of the composite dramatically [3,5,6]. For this reason, automated fiber placement (AFP) was proposed as an extension to ATL for fabricating composites with arbitrary surfaces [6,7]. Instead of laying a single tape in ATL, heated fiber tows (12 to 32) are placed onto molds with desired orientations side-by-side and simultaneously. A pressure roller reinforces the placed fibers in situ [1,3,7]. Con-

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sequently, AFP becomes to the most widespread composite manufacturing technique because of the increasing demand for complex structural components [6].

The fiber placement process can be implemented by using either specifically designed machines or robotic systems, which are redundant in this application [3]. In the first case, general CNC machines equipped with specific placement head are used. They have no limitations on the workpiece size, but usually are quite expensive and require large work floor areas [7–9]. Compared to the process-dedicated machines, the robotic systems are relatively cheap and flexible allowing changing the product type easily [9]. In comparison to their size, they can provide a large working area. Industrial robotic systems are usually composed of a 6-axis serial robotic manipulator, a specific fiber placement end-effector and an actuated positioner with one or two degrees of freedom [10,11]. The workpiece is mounted on the positioner flange and changes its orientation with rotation of the positioner axis.

In robotic fiber placement process, manipulator motion planning is an important issue. The main difficulty here arises because of robotic system redundancy with respect to the manufacturing task. To generate the desired motion, it is required decomposing the given task into a robotic manipulator motion and a positioner motion. In literature, several works deal with this issue. A conventional way is based on redundancy resolution via the generalized inverse (pseudo inverse) of the kinematic Jacobian [12–15]. It gives a unique solution for the differential kinematic equations in the sense of least squares, which corresponds to the smallest Euclidean norm of the displacement vector in the joint space. However, this technique can hardly generate the time-optimal solution taking into account velocity and acceleration constraints of actuators, which are quite important in real-life industrial applications. Another approach of motion planning for redundant robotic system [16,17] is based on the idea of "master-slave", where the trajectories of the "master" manipulator are assigned firstly, and the corresponding conjugate trajectories of the "slave" are then determined. This method is rather simple and computationally efficient, but assigning the master trajectory is not trivial, especially for complex shape objects. Besides, here it is not possible to take into account the actuator constraints in an explicit way.

To generate the manipulator motion for complex shape workpiece taking into account constraints imposed by the actuators and avoiding collisions between the workcell components, several alternative methods have been developed that are based on direct optimization of an objective function describing the total travelling time, the trajectory smoothness, the quantity of manipulator motions, etc. One of such techniques [18,19] is based on transformation of the original continuous time-optimal problem into a discrete one, where the robotic manipulator and the positioner joint spaces are discretized and the desired trajectory is represented as the shortest path on the corresponding graph. Then, the conventional discrete optimization techniques are applied to obtain the approximate time-optimal trajectory. A key issue here is related to assigning distances between the adjacent nodes of the graph, which are usually computed considering the velocity constraints only and omitting the acceleration constraints. The latter may lead to an optimal solution that corresponds to non-smooth manipulator trajectories, with essential oscillations in actuator velocities. Besides, conventional methods (Dijkstra algorithm, etc.) are rather time consuming for discretization steps acceptable in practice. Slightly different approach was proposed in [20–23] for the applications with constant Cartesian speed of the technological tool (robotic laser-cutting, spraying and arc-welding). In this case, the travelling time between the adjacent graph nodes is constant, so the required distances may be defined as the largest increments in the joint coordinates corresponding to the node-to-node movements. This allows to reduce oscillations in actuator velocities and to improve the trajectory smoothness, but the basic assumption of these techniques (constant tool speed) is not valid for the fiber placement. Nevertheless, some ideas from the above mentioned works, such as application of dynamic programming and elimination of nodes sequences violating the acceleration constraints, are useful for the problem studied in this paper.

For the fiber placement process, the problem of the manipulator motion planning was studied by Martinec [24] and Mlynek [25], who also assumed that the tool velocity is constant. Another work [26] focuses on the tool path optimization in Cartesian space while the optimal utilization of the robotic system redundancy was replaced by smoothing the end-effector trajectory. Obviously, this kinematic improvement does not allow using full capacities of the actuators, but it contributes to the trajectory smoothness in the configuration space and manufacturing efficiency by minimizing variations of the joint coordinates. To the best of authors' knowledge, there are no techniques directly addressing the problem of the time-optimal motion planning for robotic fiber placement and it is still an open issue.

Besides optimization of the travelling time, improvement of the manipulator motion smoothness is another important issue in fiber placement applications. Smooth trajectories allow considerable reduction of vibrational phenomenon and mechanical wear of the robotic system. Known techniques in trajectory smoothing focused mainly on bounding the jerk value (defined as the derivative of the acceleration with respect to time) during the trajectory planning. For example, the maximum absolute value of the jerk is limited in [27–29], and the integral of the squared jerk along the trajectory is minimized in [27,30–33]. Among the known works, it is also worth mentioning [30,31] where an efficient minimum time-jerk trajectory planning algorithm was proposed for non-redundant robotic manipulators. However, these techniques cannot be directly applied to the motion planning for the redundant robotic system.

This paper focuses on optimization of manipulator motions in redundant systems taking into account two main objectives: (i) total travelling time, and (ii) trajectory smoothness. The proposed algorithm is an enhancement of our previous technique [34], it is based on the search space discretization and relevant combinatorial optimization search. In order to reduce computing time, the algorithm is composed of three stages: rough search, local optimization and smoothing. First, the original problem is presented as a combinatorial one after a rough discretization of the search space, and it is solved by using dynamic programming. An initial solution is generated quickly here. Then, the initial solution is sequentially improved