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Research paper

Simultaneous path placement and trajectory planning optimization for a redundant coordinated robotic workcell

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ABSTRACT

An optimization method using Particle Swarm Optimization (PSO) is introduced in order to simultaneously optimize the trajectory planning and placement of a given path in a redundant coordinated robotic workcell. The workcell consists of a 6 Degree Of Freedom (DOF) serial manipulator, a 6 DOF parallel manipulator and a rotary table mounted on the parallel manipulator. Since the workcell has 13 DOF, one has to solve the kinematic redundancy of the workcell. The solution will be obtained considering the singularities of the serial manipulator and the workspace boundaries of all manipulators. The algorithm to obtain the optimum path placement is explained through a simple example and the result for a helix path around the workpiece is represented.

1. Introduction

Due to composites' light weight, high stiffness, and high strength, they have found applications in many areas, including aerospace, automobiles, wind turbines, and civil infrastructures. The increasing use of composites gives rise to the need to improve their method of manufacturing. Composite structures are typically manufactured using labour-intensive methods such as hand lay-up. However, this technique has many disadvantages, such as poor repeatability, a significant amount of wasted materials, and long process times. The advent of automated tape placement and Automated Fiber Placement (AFP) machines has significantly improved the manufacturing of composites in terms of speed of material deposition, repeatability, good compaction, reduction of waste, and seamless transfer from design to manufacturing.

1.1. Automated fiber placement

AFP machines have been used to make the fuselage of Boeing 787s and components of many aircraft structures [1,2]. Current AFP machines are generally built for manufacturing airframe components that are shaped like shallow plates or shells. Normally, they have a 6 Degree Of Freedom (DOF) Serial Manipulator (SM) in order to place the fiber on the workpiece and a rotary table to spin the workpiece. For certain applications where the shapes are more complex, such as tubes with double curvature, some modifications must be made to extend the machines' capabilities. One possible way to increase manufacturing flexibility is to add another 6 DOF manipulator to the workcell. Due to the heavy weight of the piece and

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other advantages of parallel mechanisms [3–7], we have chosen to use a hexapod Parallel Manipulator (PM) in this work. The hexapod is a classic design for position and motion control, and is often used in flight simulation [8,9]. Mounting the rotary table (1 DOF) on the 6 DOF hexapod permits maximum freedom in operation. The 6 DOF SM thus enables a 13 DOF coordinated robotic workcell to do the fiber placement task.

The quality of the end product – the composite – is largely dependent on how the original fiber path is generated [10,11]. Before we can build a framework for collaboration between a 6-DOF hexapod and a SM, we must first analyze the robots' kinematics. It is essential to solve the Inverse Kinematic Problem (IKP) and Forward Kinematic Problem (FKP) of both robots in order to control them. The main concern of this paper is to obtain the optimized motions for the aforementioned 13 DOF workcell.

1.2. Redundancy resolution

In this work, we use the term "robot coordination" to mean a collaboration between two or more robots that leads to a high degree of redundancy in the workcell. In [12], an analytical methodology for computing the inverse kinematic problem for 7 DOF redundant manipulators is proposed. The Jacobian matrix of redundant manipulators has a non-empty null space. Manipulability is enhanced by taking advantage of the null space in [13]. Efficient use of the null space enables other types of subtask resolution to be done, such as torque optimization [14], obstacle avoidance [15,16], and singularity avoidance [17,18].

Jacobian-based redundancy resolution is applicable to dynamically tracking the trajectory of the robot. In [19], the author minimizes the joint torques by choosing the joint acceleration null-space vector. In [20], the authors derive the inverse dynamics for an actuated redundant 3-DOF PM by optimizing the driving force using the least squares approach. Various artificial intelligent methods are proposed by Zhang and Lei [21] to solve the IKP of an actuation-redundant 3-DOF PM, such as Multilayer Perceptron Neural Networks (MLPNN), Radial Basis Functions (RBFNN), and Support Vector Machines (SVM). In [22], the authors present a novel approach to on-line collision-free path planning of a two-arm manipulator system. They implemented a system that generates a collision-free path for one manipulator while the other is moving.

1.3. Workpiece placement

Workpiece placement is always subject to redundancy, even in the presence of just one manipulator. The degree of redundancy in the workpiece placement is independent of the robot DOF and can be higher than the robot DOF. In [23], the goal is to determine the optimum placement of the workpiece to be machined, considering the elastostatic model of the robot and the cutting forces applied on the tool. In [24], a redundancy resolution for polishing operations is suggested. The kinematics capability is chosen to be the speed ratio of the effector, since they wanted to obtain voluntarily non-isotropic behavior. In [25], multi-objective path placement optimization for PMs is done in order to minimize actuator torques, energy consumption, and shaking forces. It is argued in [26] that it is more efficient to perform the milling operation in regions of the robot's workspace where manipulability is highest. Therefore the best initial pose of the robot is obtained to maximize manipulability. In [27], the authors numerically solved the problem of path placement for redundant manipulators. This included the problem of where to place the components (tables, other robots, or machining stations) relative to each other, as well as how to resolve the redundancies of the workcell. None of the aforementioned studies considers the path placement for a coordinated redundant robotic workcell that has a second manipulator detached from the main manipulator. They all place the path on a fixed platform rather than a moving platform. Furthermore, they neglect to perform the trajectory optimization simultaneously for both the main manipulator and the redundant manipulator.

In more recent literature [28–30], the authors propose an approach to optimize the path planning of a robot and positioner in a redundant workcell for a fiber placement task. Time-optimal profiles for the joint variables are obtained by discretizing the problem, wherein all possible motions of the robot and positioner are represented as directed multi-layer graphs. This technique is based on the discrete dynamic programming principle, which allows finding the global optimum by sequentially solving all possible sets of the problems of lower dimensions. However, since the workspace of the positioner is discretized, for each motion of the positioner, the time-optimal solution is obtained by reducing to analysis of the preceding node at each step. Furthermore, the method does not take the placement of the positioner and the path on the positioner into account. The goal of [28–30] is one part of the objective of this paper. This part will be referred to as the 1D optimization, i.e. optimization of the rotary table's motion.

The same objective of fiber placement redundancy resolution is investigated in [31,32]. They obtain the optimal trajectory for rotary table by the means of Gradient Projection Method (GPM). GPM is a powerful tool when it comes to 1 DOF redundancy resolution, but for higher DOF workcells, it can only result into local optimums.

In this paper, we intend to optimize the path placement of a redundant coordinated robotic workcell, Fig. 1. Assuming that the path is given using the method represented in [31,32], it is possible to place it anywhere within the workspace boundaries. In this paper, a path is a set of time-independent frames in the Cartesian space given in the form of a text file (each line in the file has 16 entries representing 16 elements in the 4 by 4 homogeneous transformation matrix) and a trajectory is the motion in space (either Cartesian or joint space) relevant to each frame in the path. The optimization problem is to find the best place to put the path in order to satisfy the optimization criteria. As shown in Fig. 1, the coordinated workcell consists of an SM, a hexapod PM, and a rotary table mounted on the hexapod. The workpiece to be