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Task scheduling and motion planning for an industrial manipulator

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ABSTRACT

In many robotic industrial applications, a manipulator should move among obstacles and reach a set of task-points in order to perform a pre-defined task. It is quite important as well as very complicated to determine the time-optimum sequence of the task-points visited by the end-effector's tip only once assuring that the manipulator's motion through the successive task-points is collision-free.

This paper introduces a method for simultaneously planning collision-free motion and scheduling time-optimal route along a set of given task-points. This method is based on the projection of the workspace and the robot on the B-Surface to formulate an objective function for the minimization of the cycle time in visiting multiple task-points and taken into account the multiple solutions of the inverse kinematics and the obstacle avoidance. A modified GA with special encoding to encounter the multiplicity of the robot inverse kinematics and the required intermediate configurations is used for the searching of the optimal solution on the B-Surface.

The simulation results show the efficiency and the effectiveness of the proposed approach to determine a suboptimal tour for multi-goal motion planning in complex environments cluttered with obstacles.

1. Introduction

In manufacturing, high productivity demands the completion of robot tasks in the minimum possible time. On the other hand, today's production lines usually incorporate robots that interact with a wide range of equipment and fixtures. Thus, considerable attention has been paid to applications, where the manipulator's tip is assigned to reach a sequence of task-points only once in the minimum total cycle time, while operating in an environment cluttered with obstacles. It is very important to solve this problem for many robotic applications in manufacturing, such as pin assembly, insertion of electronic components, multiple drilling, spot welding and inspection tasks. Programming these capital intensive installations can be made off-line in powerful robot simulation systems for reducing the setup cost. Therefore software tools integrated in the simulators for determining the minimum cycle time sequence of given task-points could provide considerable support to the programmer, reduce the programming and setup time as well as the production time and cost.

The present work introduces a new method for solving the multi-goal motion-planning problem for an industrial manipulator operating in a 3D environment cluttered with static obstacles and serving a set of task-points with point-to-point motion. The above combined problem (motion planning problem and task scheduling problem) is formulated over the Bump-Surface [1] concept into an optimization problem, where the optimum sequence of the task-points should be determined towards cycle time minimization and simultaneously a collision-free motion of the manipulator between the obstacles should be obtained.

Using the Bump-Surface (B-Surface) concept the 3D manipulator's workspace is represented by a 3D surface embedded in $\mathfrak{R}^4$, which captures both the free-space and the forbidden areas of the manipulator's workspace. A global optimization problem is then formulated considering simultaneously the task-scheduling and the collision-free motion planning of the manipulator among the obstacles. The optimization problem is solved using a Genetic Algorithm (GA) with a special encoding that considers the multiplicity of the Inverse Kinematics that introduced in [2]. In this work, this encoding is extended to incorporate the intermediate configurations necessary for optimal collision-free motion.

1.1. State-of-the-art

The problem of optimal multi-goal motion planning for an industrial manipulator operating in 3D environments cluttered with obstacles can be considered as the coupling of the task scheduling problem and the motion planning problem between successive task-points. Since each end-effector pose can be

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reached by a finite number of configurations for a non-redundant manipulator, a valid sequence consists of a series of configurations where only one configuration is taken from each pose of the end-effector (task-point).

In the task scheduling problem, the optimum sequence of a manipulator's tip visiting a number of task-points is determined. This problem is a variant of the well-known Traveling Salesman Problem (TSP) [3], but it is much more complex. According to the classical TSP, the objective is to determine the optimal tour through a pre-specified number of cities provided that the salesman visits each town exactly once. Adapting TSP to Robotics, the measure to be optimized is time instead of distance, which considerably depends on the multiplicity of manipulator configurations corresponding to one pose (position and orientation) of the end-effector. In addition, the travel cost between the stations is not given or easily obtained since the obstacle avoidance should be encountered too.

The majority of the published methods for the solution of the motion planning problem (MPP) for manipulators [4] are based on three main approaches: cell decomposition, potential field and skeleton methods. The MPP is usually formulated in terms of the Configuration Space (C-Space), which is the space of all possible configurations of the robot [5]. In the C-Space, each configuration of a manipulator is represented by a point and the obstacles are transformed appropriately. For the case of an articulated manipulator with n degrees of freedom, the dimension of the corresponding C-Space is n. Thus, the motion planning problem becomes equivalent to the motion planning of a point-robot in n dimensional C-Space that has been proven to be an NP-hard problem [6].

Many methods and algorithms have been introduced for the solution of TSP with a large number of cities as well as for motion planning of mobile robots and manipulators. However, only few research groups have worked on the solution of the multi-goal motion planning and scheduling problem for manipulators or coordinate measuring machines moving in a workspace cluttered with obstacles.

Spitz and Requicha [7] investigated the multiple-goal path planning problem in the context of Coordinate Measuring Machine (CMM), which is considered as a Cartesian 3-*dof* robot. The obstacles in this domain are the part to be inspected, the CMM table and the fixturing elements. The CMM path planning problem is to generate an efficient and collision-free path for the CMM to inspect a collection of points. In other words, the problem is to find the shortest tour of the given goal configurations or notify that such a tour does not exist. The proposed planner is based on the probabilistic roadmap planner (PRM) to construct a roadmap, where the nodes are the goal configurations and each pair of nodes is connected by an edge that represents an optimal path. The next step is to extract a near-optimal tour from the roadmap. Their main problem was the need for expensive robot simulation software and parallel computing architectures. The CMM problems considered in this work are formulated in a quasi-static, low dimensional configuration space, which leads to low computational time. Moreover, the assumption of fixed configurations at the inspected points limits the number of configurations from which a probe can measure a point and therefore limits the complexity of the problem.

The multi-goal path planning (MTP) described in [8] tries to avoid computing a collision-free path between every pair of goals. Both, the robot and the obstacles are provided as computer-assisted design (CAD) models. Their approach consists of three major modules (embedded in a main control loop): MTP Control, MTP Path Planning and Shortest Sequencing Planning. The MTP Control consists of selecting the suitable start and goal configuration pair of the MTP Path Planning in every iteration. To this end, four different selection methods are proposed and compared. After selecting pairs of goals, it computes a collision-free path between each pair and runs the TSP algorithm. A genetic algorithm that takes goal groups as inputs generates optimized tours. This technique is inherently limited to searching low-dimensional configuration spaces, and hence restricts the range of problems that the planner can handle [10].

The same authors continued their work [9] by formulating an optimally discretized implicit C-space, which was searched by an A* algorithm. A bidirectional search was parallelized to reduce the computational time in minimizing the total path length of the manipulator collision-free tour between the given goal poses. The authors admitted that in larger search spaces, with a slight change of the obstacle location the fine discretization would lead in memory overflow. Thus, they investigated three different methods to determine the discretization resolution

The algorithm proposed by Saha et al. [10] operates under the assumption that finding a good tour in a graph with edges of given costs takes much less time than computing good paths between all pairs of goal configurations from different groups.

They proposed a lazy algorithm that calls the motion planning solver between two configurations when it is necessary. Thus, the algorithm initializes the distance between every two configurations from distinct goal groups and then runs once to find the near-optimal tour. So, the algorithm balances the time spent in computing paths between goal configurations and the time spent in computing tours. However, it still remains a question whether the provided solution is the global optimum.

The authors in [11] tackle the problem presented in [2], by also taking into consideration the placement of robot. This information has been incorporated to the metric used for the determination of the minimum cycle time. Although the authors in [12] do not tackle the optimization of the path planning problem, they use the Manhattan distance as a measure of the total actuator movement required to move in a direct path between the two configurations. This approach works under the idea that the lowest cost between two configurations is the straight line path and concentrates on determining the lowest cost path between two poses: an initial configuration and all of the possible goal configurations. Although the generated paths are not optimal, this approach is well suited to applications, where a mobile manipulator where the surrounding terrain changes at each step.

In contrast to other existing path planning methods, our algorithm searches for global optimal solutions and tackles the problem of how the robot moves between goal configurations in an environment cluttered with obstacles. The paper at hand is an extension of the work presented in [2], where the optimum sequence of task-points visited by a robot is searched in an environment free of obstacles.

1.2. Main contribution

The main innovations and contribution of the proposed approach are the following:

i. The workspace is not discretized but is presented as one entity analytically. The determination of the B-Surface is very fast and independent of the manipulator [1].
ii. The C-space transformation (Implicit or explicit) is not necessary, since the searching is performed on the B-surface. There is no need for high storage capacities since the entire workspace is represented by an analytical expression.
iii. Simultaneous solution of the motion planning and scheduling is achieved, since both problems are handled as a global optimization problem. The solution of the motion planning problem for all the possible pairs of the given configurations can be