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Abstract

This paper is concerned with introducing a genetic-based algorithm for the minimum-time trajectory planning of articulated robotic manipulators. The planning procedure is performed in the configuration space and respects all physical constraints imposed on the manipulator design, including the limits on the torque values applied to the motor of each joint of the arm; consequently, the complete non-linear dynamic robot model is incorporated in the formulation.

I. Introduction

Trajectory planning of mechanical manipulators requires providing a time-history of motion for the arm to accomplish a required task. However, since an infinite number of solutions exist to move from one point to another, a suitable minimum-time trajectory must be found to achieve high-productivity in a particular application. The established approach of searching amongst pre-defined finite grid points is sub-optimal and is very difficult to achieve in real-time.

The attractive attributes of genetic algorithms [1] motivated several investigations into the applications to robot path planning [2]. However, none of these investigations acknowledges the limitations imposed on the manipulator by design, thus rendering the developed approach as inefficient for real-world systems. In this approach, the main aim is to provide an efficient planning algorithm in terms of execution time while respecting the limitations imposed by design.

II. The Exhaustive Search Algorithm

The established and commonly used approach to minimum-time robot motion planning employs a heuristic exhaustive technique to search the work space of the arm. The main idea of the algorithm is to tessellate joint space into a grid of possible motion nodes, where at each option node, given the position and velocity at the previous node, possible velocity values are constrained by the time optimality together with the dynamics of the arm. A tree of all possible state-space paths can be constructed and then searched for the minimum-time one. The most comprehensive formulation is reported by Sahar and Hollerbach [3] where two distinct global and local solutions are used to compute the travelling time between nodes, and achieving the correct transition velocities and corresponding torques.

However, the long-standing drawback in the above approach is the difficulties with searching infinite space, in particular when a large grid is on hand. Nonetheless, being the ultimate solution, it provides the best benchmark for testing any results obtained from the genetic-based approach.

III. Robotic Path Planning using GAs

Robot trajectories consists of a finite sequence of position, velocity and torque values. Since the intention is to obtain a minimum time arrangement of joint angles together with the relevant actuator inputs at each node, it is suitable to code these into a string of the format

$$\{\alpha_{11},\alpha_{21},\ldots,\alpha_{m1},s_1;\alpha_{12},\alpha_{22},\ldots,\alpha_{m2},s_2;\ \ldots..\ ;\alpha_{1n},\alpha_{2n},\ldots,\alpha_{mn},s_n\}$$

where α_{ij} is the *jth* intermediate position node of the *ith* link, n is the number of intermediate position nodes, and s_j is the torque bound information associated with the travelling from (j-1)*th* to *jth* node. The arm therefore moves from rest from the start node α_1, assuming s_1 torque bound information, successively through each and every node in the same manner, and arrives at the end node α_n constrained by the system dynamics and bringing the arm to rest again.

The fitness of a string is assigned the negative value of the time required to move from the start node to the end node. After decoding, the phenotypic parameters of each position node will be passed to the objective function to compute the time travel from one node to another, which is evaluated by scaling a formulation of the inverse dynamics equations of motion. Finally, the total travel time is the sum of all individual transition time values.

IV. A Variable Length Genetic Algorithm

The variable length genetic algorithm developed was targeted at a two link manipulator as an initial study, where the motion space is divided into a nxn grid. The initial population is generated using a relative transitional scheme as shown in Figure 1, where, from any one node, the arm is restricted in moving to only nine neighbouring nodes. The space was tessellated such that a transition has higher probability of moving towards the end point, and at any one time only one joint is allowed to move away from the final position. A simple algorithm was developed, incorporating this relative transitional scheme, to generate trajectories such that they will always arrive at the desired final position.

An initial population of trajectories starting from the start position and ending at the final position can be generated using the above algorithm. During *reproduction*, the number of occurrences of the same trajectory selected for crossover is limited, which encourages higher interaction among different trajectories. In addition, to prevent any path dominating the population leading to pre-mature convergence, only a specific number of copies of the same trajectory are allowed to remain in the population after reproduction, and extra copies are replaced by new trajectories.

Analogous crossover [4] is used, where single point crossover was adopted as an initial study. After choosing a cross site in one parent string, the corresponding cross site in the second parent is determined according to the proximity the parameters have in the phenotype space. To further prevent irrational crossing of two trajectories, crossover is performed only if the second crossing site is within the proximity defined by the circle centred at the first crossing site whose radius is a design parameter.

Mutation is needed to keep the pot boiling. The *destroy trajectory operator*, when active, replaces the selected trajectory with a randomly generated one, giving rise to new search space. Another mutation operator, the *position operator*, varies slightly the position of one or more nodes in a path, and is motivated by the findings that neighbouring paths generally have slightly varied performance. This operator thus helps to find trajectories which may or may not be better around a 'good' trajectory found by the crossover operator. The *dynamic operator* performs modification of torque bound information on one or more nodes of a trajectory. Being uncorrelated with the positional information, optimum torque bound information can only be found by random mutation.

V. Results and Discussion

The variable length genetic algorithm shows great potential in solving the robot path planning problem. It can find a good minimum-time path within a much shorter period of time as compared to the heuristic search method. Figure 2 shows the optimum solution for a trajectory travelling from (-0.5,-1.0) rad to (0.5,1.0) rad in a $10x10$ grid tessellation. The simulation travelling time and execution time were 0.79 seconds and one hour, respectively. The results were obtained by running the algorithm with a constant population size of 100 in each generation iterated for 5000 times. With the same grid size, the heuristic search technique took more than 20 hours to compute a travelling time of 0.80 seconds.

The radius defining the circle for crossover was found to be an important parameter in promoting sensible crossover. When it was set to 1.0, which effectively allows crossover to be performed in any circumstances, the algorithm found the best solution of 0.80 seconds in the 205*th* generation and with no improvement in future generations. However, when a radius of 0.25 was used, the above reported optimum result (i.e. 0.79 secs) emerged in the 4717*th* generation.

VI. Conclusions

The reported algorithm emerged through an evolutionary process while taking account of different concerns related to robot motion planning. Reproduction was controlled to prevent pre-matured convergence, the analogous crossover directed sensible crossover operations, and specially shaped mutation operators promoted new search space. The algorithm was proven to be far more efficient compared to the conventional heuristic search technique with a reduction in the execution time of 1:20. Although results are presented for a simple two-link manipulator, the algorithm is readily applicable for any number degrees-of-freedom.

In this pioneering stage of the research, genetic-based approach to robot motion planning shows great potential where the results suggest that the performance of this algorithm may be substantially improved with further development, and investigations continue to enhance the parameters used. Furthermore, to present a realisation for on-line application, a distributed form of the genetic algorithm is currently pursued by the group.

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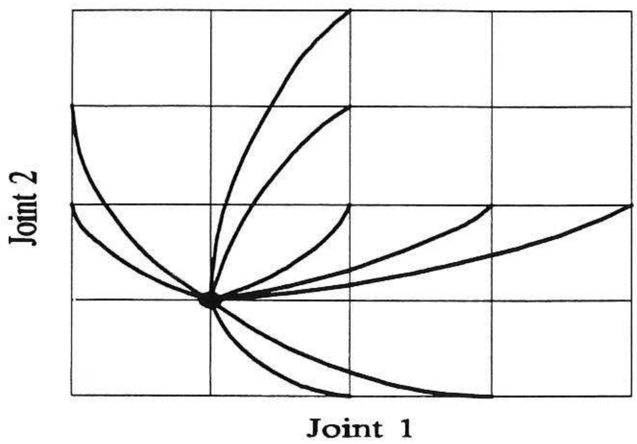

Figure 1: Relative transition scheme.

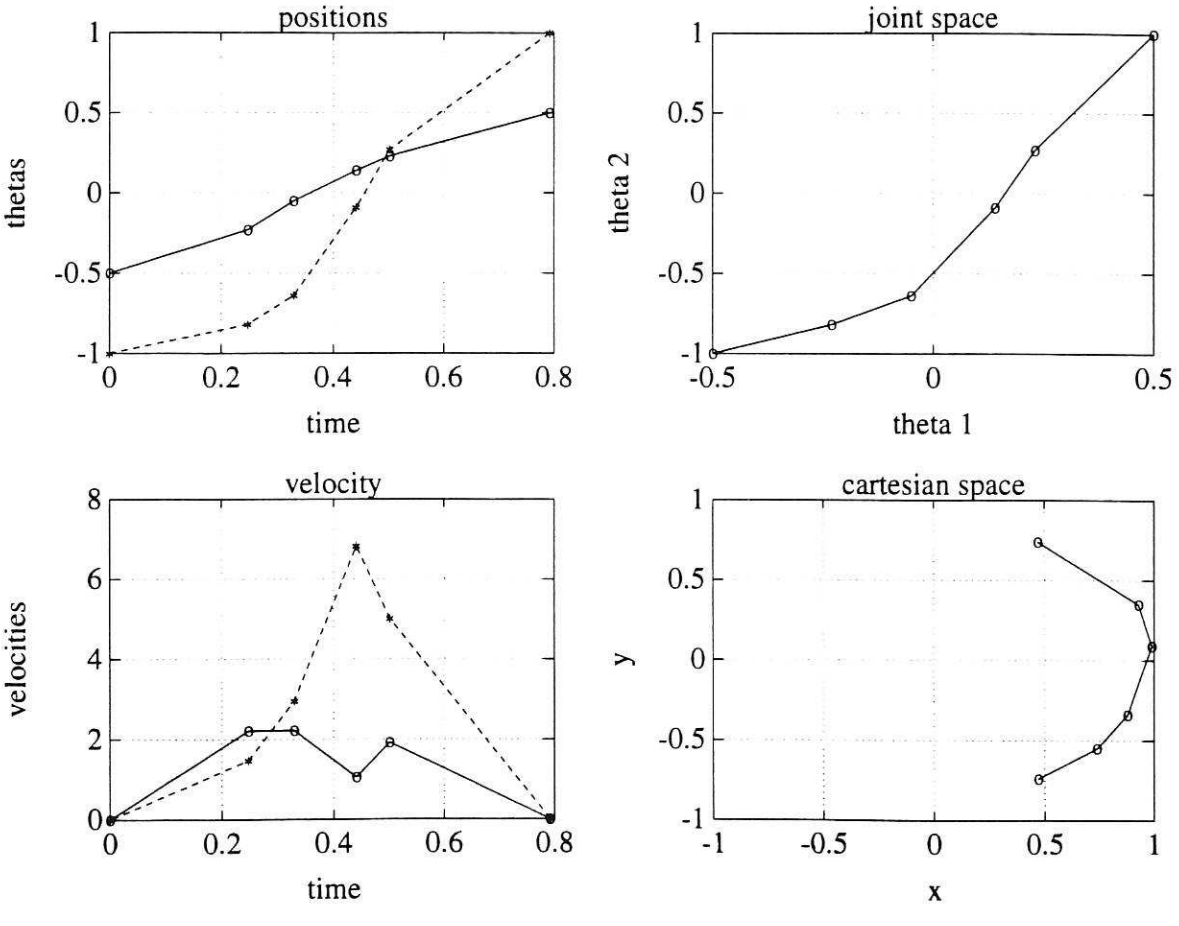

Figure 2: Optimum trajectory evolved after 5000 generations with 100 individuals in each generation; Joint one (——) and joint two (----) in a 10x10 grid space.