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Technical Paper

Dual hierarchical genetic-optimal control: A new global optimal path planning method for robots

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ABSTRACT

A new two-stage analytical-evolutionary algorithm considering dynamic equations is presented to find global optimal path. The analytical method is based on the indirect open loop optimal control problem and the evolutionary method is based on genetic algorithm (GA). Initial solutions, as start points of optimal control problem, are generated by GA to be used by optimal control. Then, a new sub-optimal path is generated through optimal control. The cost function is calculated for every optimal solution and the best solutions are chosen for the next step. The obtained path is used by GA to produce new generation of start points. This process continues until the minimum cost value is achieved. In addition, a new GA operator is introduced to be compatible with optimal control. It is used to select the pair chromosomes for crossover. The proposed method eliminates the problem of optimal control (being trapped in locally optimal point) and problem of GA (lack of compatibility with analytical dynamic equations). Hence problem is formulated and verification is done by comparing the results with a recent work in this area. Furthermore effectiveness of the method is approved by a simulation study for spatial non-holonomic mobile manipulators through conventional optimal control and the new proposed algorithm.

1. Introduction

Although optimal path planning of robots has been developed recently, but still there is not a comprehensive algorithm for finding the global optimal path. Optimal path planning algorithms are classified as below: evolutionary and analytical, but both of them have some problems. In the first group, there is no need for gradients of cost function. The optimal path is found by generating random points all over the possible search area, comparing value of cost function in these points and then selecting the best set of points. Random search techniques like annealing simulated, genetic algorithm and neural network methods [1,2] are in this category. In the second group, the analytical gradients of cost function are used for the optimization process. The dynamic programming [3], direct optimal control [4,5], Taylor series complex expansion [6] and indirect open loop optimal control [7,8] are at this category. In these methods, optimal values are obtained after calculating derivatives of the cost function using a first- or second order algorithm. derivatives of the cost function are calculated according to the design variables. In the first-order algorithms, only first derivative of the cost function is necessary with respect to design variables. For example, the fastest gradient-based algorithm is a first-order algorithm method. In this algorithm, the search is performed in the negative gradient vector direction. Second-order algorithms need both the cost function first derivative and second derivative values. Algorithms of pseudo Newton [9] are of this type.

Wang et al. have solved the optimal control problem using the B-Spline functions in order to determine the maximum payload of a fixed-base manipulator [12]. The basic idea of this work is to parameterize the joint trajectories by the use of B-Spline functions, and tuning the parameters in a nonlinear optimization until a local minimum that satisfies the constraints is achieved. A weak point of this method is limiting the solution to a fixed-order polynomial. Another difficulty arises from the complexity of differentiating torques with respect to joint parameters and payload due to their constraints and discontinuity. Constantinescu and Croft [10] introduced a method to determine smooth and time-optimal path constrained trajectories for robotic manipulators using the third derivatives of path parameters. The desired smoothness of the trajectory is obtained through imposing limits on the torque rates. The optimization problem is solved using the flexible tolerance method. But, the method may return a local minimum and it is not applicable for holonomic or non-holonomic systems. A method for trajectory planning using the notion of kinematic controllability for second-order underactuated mechanical systems is presented in [11], that it obtains an optimal time solution and the others

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Nomenclature

O	the center of the world coordination system
b	the distance between driving wheels and axis of symmetry
r	the radius of each wheel
l_1	the length of first link
l_3	the length of third link
θ_r	the angular displacement of the right wheel
θ_1	the angular displacement of the first link from the mobile platform
θ_3	the angular displacement of the second link from the second link
τ_2	the torque exerted to the right wheel
τ_3	the torque exerted to the first joint
τ_5	the torque exerted to the third joint
ϕ	the heading angle of platform measured from X-axis of the world coordinates
J_0	the moment of inertia of the mobile platform without the driving wheels about a vertical axis through o
J_1	the moment of inertia of the first link about a vertical axis
J_3	the moment of inertia of the third link about a vertical axis
m_1	the mass of the first link
m_3	the mass of the third link
m_w	the mass of each driving wheel plus the rotor of its motor
m_p	the mass of payload
$V(q, q')$	$n \times n$ non-linear terms matrix
M_m	manipulator inertial matrix
m_a	mass at the tip of the link 1
t_0	initial time
o	the intersection of the axis of symmetry
c	the center of mass of mobile platform
d	the distance from c to o
l_2	the length of second link
θ_l	the angular displacement of the left wheel
θ_2	the angular displacement of the second link from the first link
(X, Y)	the coordination of center of mass c in the world coordination system
τ_2	the torque exerted to the left wheel
τ_4	the torque exerted to the second joint
J_w	the moment of inertia of each wheel and the motor rotor about wheel axis
J_2	the moment of inertia of the second link about a vertical axis
m_2	the mass of the second link
m_0	the mass of mobile platform without driving wheels
$M(q)$	nn inertial matrix
$E(q)$	$n \times r$ fix matrix
w_i, r_i	weighting matrixes
τ_m	joint torques vector
t_f	final time

path parameters are ignored. Gyorfi et al. [13] developed an evolutionary method of planning paths subjected to sub-path constraints. This method involves a fixed-length chromosome formulation of a genetic algorithm that utilizes exiting operators and a new subpath reversal operator. Ching-Chih et al. [14] presented a parallel elite genetic algorithm for application in global path planning of autonomous mobile robots navigating. Macfarlane and Croft [15] used a concatenation of fifth-order polynomials to provide a smooth trajectory between two way points. The methods of [13–15] have not considered dynamic equations of system and they have not investigated the feasibility of the path, dynamically. Xin et al. [2] proposed a method for global path planning based on neural network and genetic algorithm. They constructed a neural network model from environmental information to prevent collision between robot and obstacles in workspace. This method could not be used for cost functions containing velocity and torque of joints. Ferguson and Stentz [16] presented an interpolation-based planning and replanning algorithm for generating low-cost paths through uniform and non-uniform resolution grids. The proposed methods of [15,16] have not considered dynamic equation also. Korayem et al. [7,8] solved a path planning problem that maximized load carrying capacity and minimized a cost function by indirect open loop optimal control. Gregory et al. [17] studied energy-optimal trajectory planning for manipulators with holonomic constraints. Their method involves a numerical resolution of a constrained optimal control problem with dynamic equations. The methods of [7,8,17] obtain local minimum.

Some previous works which are done without considering dynamic equations are not valid for minimizing torque and energy in robots. To deal with the problem of optimizing dynamic related parameters like velocity and torque, one need to consider dynamic equations. But being not compatible with discrete evolutionary methods, applying global optimization methods like GA is difficult for dynamic equations. Author's recent investigation showed that using evolutionary methods for path optimization of robots considering dynamic equations does not guarantee to achieve proper result, as kinetic equations are analytical and not suitable for evolutionary methods. Hence the best methods are those with analytical procedure like optimal control. This group of methods suffers from lack of ability to find global optimal path. Therefore authors decided to use a new iterative method with benefits of both evolutionary and analytical methods. To create interface with analytical dynamic equations, optimal control is employed and to search all possible start points for optimal control, a new developed genetic algorithm is recruited. Authors believe that, it is the best way for global motion planning of robots with taking into account kinetic parameters.

One of methods for path planning of a robot, considering the dynamic equations, is an analytical indirect optimal control that some works was pointed in pervious works section. This method gives local minimum but in this paper another part is added to the method for obtaining global minimum. The most contribution of this paper is adding an evolutionary algorithm to the analytical indirect optimal control and obtaining global minimum of cost function. Evolutionary method is based on genetic algorithm. In GA, a new *selection* operator to select appropriate paths for *crossover* operator is defined and this is another contribution. In addition to, other GA operators are defined in new form. In comparison to other methods, some advantages of this approach are:

- Achieving global minimum
- Applicability for systems with non-holonomic constraint in dynamic equations.

The cost function is defined and the Hamiltonian function is formed. Then, the necessary condition is obtained relaying on Pontryagin's minimum principle. Some start points are generated by GA as first stage. Then they are used by optimal control as second stage of optimization. Then sub-optimal path is delivered to GA again to use it for searching all possible data and producing new optimal generation and delivering to optimal control. This process is continued until a path with minimum cost is achieved using polynomials