Obstacle Avoidance Control of Redundant Robots using Genetic Algorithms

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ABSTRACT
In some daily task operations for an industrial robot manipulator such as pick and place, it is desired to minimize its hand tip positional error when moving the robot from one location to another. Such tasks become more complex in environments cluttered with obstacles, since the constraint for collision-free movement must be also taken into account. This paper presents a new technique based on genetic algorithms (GAs) to solve the above problem. The efficiency of the proposed GA technique is demonstrated through experiments curried out on two planar robots with five and seven links, respectively.

1. INTRODUCTION

Collision-avoidance is an absolutely essential requirement for a robot to complete a desired task in an environment with obstacles. In order to achieve such complex tasks robots should be redundant, i.e. should possess at least one degree-of-freedom (DOF) more than the number required for the general free positioning. Exploiting the redundant DOF results in greater dexterity and flexibility for the robot's motion so that very complicated tasks can be tackled. To accomplish the high variety of industrial and non-industrial applications, task oriented solutions to the inverse kinematics problem of robot manipulators are necessary to be obtained. Thus, suitable task criteria should be incorporated in the formulation of the kinematics control problem.

Much effort has been devoted in the development of efficient procedures to solve the inverse kinematics problem of redundant robot manipulators. In general, this is not a trivial problem since the necessary mapping from the task coordinates to the joint coordinates is not one to one, and yields an infinity of solutions. The problem becomes harder because of the constraints related to the physical obstacles. Therefore, a complex space full of discontinuities and non-linearities must be searched for a solution.

A number of works have been appeared in the literature that use robots' redundancy to solve the inverse kinematics problem in environments with obstacles. Nakamura, Hana'usa, and Yoshikawa (Nakamura et al., 1987) introduced the concept of task priority in relation to the inverse kinematics problem for redundancy control of robot manipulators. A solution to the problem is derived taken into account the order of priority, so that subtasks with lower priority can be performed utilizing redundancy on subtasks with higher priority. Obstacle avoidance problem is solved through the use of potential functions (Khatib and Le Maitre, 1978). Klein (Klein, 1984) showed by numerical simulation that a manipulator can avoid an obstacle by paying attention to the point of the manipulator nearest to the obstacle. Maciejewski and Klein (Maciejewski and Klein, 1985) considered the problem of the inverse kinematics of redundant robots in environments with moving obstacles. The problem is formulated as an optimization problem under the constraints of multiple goals: a primary goal described by the end-effector trajectory and a secondary goal describing the obstacle avoidance criteria. Obstacle avoidance is achieved by maximizing the distance between robot and obstacle. A similar method implemented in static environments, i.e. in environments with fixed obstacles and with an a priori knowledge of the workspace has been appeared in (Yoshikawa, 1984). In an early work by Liegeois (Liegeois, 1977), the active utilization of redundancy of robot manipulators was discussed. A scheme for solving redundancy in robot arms based on the Reduced Gradient optimization method has been presented in (De Luca and Oriolo, 1991). This scheme solves redundancy by using only the extra DOF for optimization of various criteria such as manipulability, and distance from obstacles. Aspragathos and Hewit (Aspragathos and Hewit, 1983) proposed a method based on the resolved motion rate control technique (Whitney, 1972) to control the motion of a redundant manipulator moving through an access port. The robot's redundant DOF were used in a natural way to simplify the operator's task by allowing him to concentrate on the end-effector manipulation. In another work of the authors of this paper (Dermatas et al., 1994) a task oriented solution to the inverse kinematics problem of redundant manipulators based on neural networks has been proposed. To obtain an "optimum" solution to the problem, two criteria have been taken into account in the formulation of the kinematics control problem: maximization of the robot's manipulability and minimization of the joint displacement. All of the above techniques are based on the utilization of the Jacobian matrix and its pseudo inverse.

Parker, Khoogar and Goldberg (Parker et al., 1989) introduced the use of genetic algorithms (GAs) for solving the inverse kinematics problem of redundant robots. The GAs were used to position the end-effector of a robot at a target location while minimizing the largest joint displacement from the initial position. More recently (Davidor, 1991), GAs were used to automatically generate robot trajectories in environments without obstacles. Although the method produced a rather not satisfactory deviation between the programmed and the desired path, GAs seem to be a promising field in describing and optimizing such tasks.

This paper presents a new task oriented solution to the inverse kinematics problem of redundant robot manipulators in relation to obstacle avoidance. The problem is formulated as a constrained optimization problem and solved using GAs. There are several features of GAs that make them attractive for use in this problem. GAs are theoretically and empirically proven (Goldberg, 1989) to provide robust search in complex spaces with discontinuities. They are able to reach a global optimal solution in a complex search space which can be multimodal and nonlinear. Constraints related to obstacles in robot's environment require the search of such complex spaces. Furthermore, using GAs there is no need to compute the Jacobian matrix, so that any problem related to the inversion of this matrix is overcomed. In the introduced method only the forward kinematics equations of the robot are used which is a rather simple task to develop.

The remainder of this paper is organized as follows: Section 2 states the problem and presents the proposed GA solution. Section 3 demonstrates and discusses the efficiency of the proposed GA through three experiments applied on two planar manipulator with five and seven-DOF, respectively. Finally, section 4 summarizes the contribution of the paper.

2. STATEMENT OF THE PROBLEM

What configuration must a redundant robot manipulator adopt in order to place its end-effector at a desired location while avoiding obstacles in its environment ? The answer to this question is the basic aim of this work.

Throughout the paper the following assumptions are made:

- two-dimensional problems in the plane are considered
- the robot is any redundant (or non-redundant) planar manipulator
- if the robot's end-effector current position is $\underline{P}_c = [X_c, Y_c]^T$ and the desired final position is $\underline{P}_f = [X_f, Y_f]^T$, then the positional error is defined as

$$ErrorP = \sqrt{((X_c - X_f)^2 + (Y_c - Y_f)^2)} \tag{1}$$

- the end-effector's orientation can be either a given desired or can be any (free) orientation

- robot's motion is constrained within obstacles in the workspace; where obstacles are presented as convex polygons with fixed and known geometry. The boundary of a not convex polygons is represented as a union of convex polygons.

With these assumptions the problem can be typically defined as: Given an initial placement (meaning position or position/orientation) and a desired final placement for the end-effector of a redundant robot manipulator, find a collision-free configuration for the robot that places the end-effector at the desired final location with the greatest accuracy, i.e. making ErrorP (given by equation (1)) as small as possible.

2.1 Description of the Optimization Problem

Minimizing or maximizing an objective function subject to some constraints is in general the purpose of any optimization problem. In the non-linear joint displacement analysis of the inverse kinematics problem of a robot manipulator, the main objective is to minimize the positional error between two specific robot locations. Even without obstacles this problem is not trivial for redundant robots, and the presence of stationary or moving obstacles in robot's workspace makes it very complicated. Under these circumstances, the problem's main objective is to minimize the positional error and the secondary objective is to satisfy the constraints related to robot's collision-free movement, as the end-effector moves from one location to another. The aim of this paper is to show through practical experiments how GAs can be used to solve this problem. The optimization problem can be formulated as follows:

$$\begin{cases} \text{minimize ErrorP} \\ \\ \text{subject to collision-free movement} \end{cases} \tag{2}$$

or in an equivalent form

$$\begin{cases} \text{maximize } \dfrac{1}{1+\text{ErrorP}} \\ \\ \text{subject to collision-free movement} \end{cases} \tag{3}$$

In the case of equation (3) the aim is to maximize the objective function $\frac{1}{1+ErrorP}$ by forcing *ErrorP* to a minimum value, ideally zero.

2.2 The Proposed GA Solution

In this study, a simple GA (Goldberg, 1989) is used to optimize the problem given by the equation (3). There are at least four basic reasons that make GAs attractive for use in this problem: First, they are theoretically and empirically proven to provide robust search in complex spaces finding nearly global optima. In general, the constraints related to obstacles in robot's workspace generate a search space with discontinuities and non-linearities. Therefore, classical optimization methods depending upon restrictive requirements of continuity and derivative existence, and due to their inherently local scope of search are unsuitable for the solution of this problem. Second, GAs do not require any form of smoothness although the search space contains discontinuities and non-linearities. Third, they do not need the computation of the Jacobian matrix so that any problem related to the inversion of this matrix like singularities are avoided. Fourth, they allow additional constraints to be specified easily.

A critical aspect in designing a GA is the basic mechanism that links the GA to the real problem which has to be solved. This mechanism is twofold: firstly a way of *encoding* solutions to the real problem on artificial chromosomes, and secondly an *evaluation* of a function (fitness) that returns a measure of how good an encoding is. The chromosome selected for use in this work is an *m*-bit string with the following syntax: the first *m/DOF*-bits correspond to the 1^{st} joint of the robot, the next *m/DOF*-bits correspond to the 2^{nd} joint, etc. Therefore, each joint angle can be calculated from the values of its *m/DOF*-bit string using the mapping shown below:

$$\Theta_i = \Theta_i^{\min} + \left[\frac{Bitvalue}{2^{(m/_{DOF})}}\right] \cdot \Theta_i^{\max} \tag{4}$$

where, Θ_i is the variable for the i^{th} joint, and $\Theta_i^{\min}$, $\Theta_i^{\max}$ the corresponding minimum and maximum limits (depending on the robot's geometry).

In environments without obstacles the fitness function selected for evaluation is:

$$fitness = \frac{1}{1 + ErrorP} \quad (5)$$

2.3 Handling Constraints in the Genetic Search

GAs are essentially unconstrained search procedures within the given representation space. The traditional GA formulation for constrained optimization problems is through the use of penalty functions (Goldberg, 1989). Another formulation frequently mentioned in the literature is to design and apply special recombination operators that maintain feasibility. In general, which alternative from the above is best to use depends on the particular problem.

In this study, a different technique is used to manage constraints in the genetic search. Since unconstrained search techniques are considered, and taking into account the formulation of the problem given by equation (3), the following fitness function is selected for use:

$$fitness = \begin{cases} \dfrac{1}{1 + \text{ErrorP}}, & \text{if collision-free movement} \\ 0, & \text{otherwise} \end{cases} \quad (6)$$

Therefore, the objective of the proposed GA is to maximize the fitness function given by equation (6), by forcing ErrorP to a minimum value, ideally zero. This formulation of the fitness gives small score to infeasible solutions (actually a zero value) so that they have no chance to survive and therefore no hope to get copies in the next generations.

2.4 Obstacle Avoidance Control

An effective scheme based on the concept of convex hulls is used in the proposed GA to guarantee the collision-free movement of the robot manipulator. The scheme is conceptually simple but powerful enough, and has been appeared in a previous work of the authors (Nearchou and Aspragathos, 1994). This scheme is briefly described as follows:

To check whether there is a collision between a link and an obstacle it is suggested to build the convex-hull of the following set of points: the two joints of the link and the vertices of the obstacle. After the construction of the convex-hull, by simply locating the positions corresponding to the link's joints in the hull, it can be verified whether there is a collision or not. This technique is given below in algorithmic form:

For each link of the robot arm:

1. Construct the convex hull of the following set of points: the two joints of the link and the vertices of the polygon (fig. 1.a).

2. Search this hull and locate the positions corresponding to the joints of the link.

3. If no one of the joints are contained in the hull, then we have a collision (fig. 1.b).

4. If both of the joints are contained in the hull in successive positions say k and k+1, or in the first and the last position, respectively, then there is no collision (fig. 1.a), else there is a collision (fig. 1.c).

5. If only one joint is contained in the hull, check if the other joint lies outside the polygon. If this is the case, then there is no collision (fig. 1.d), otherwise a collision occurs (fig. 1.e). Polygon interior points can be easily determined using the even-odd method, or alternatively the winding-number method (Harrington, 1987).

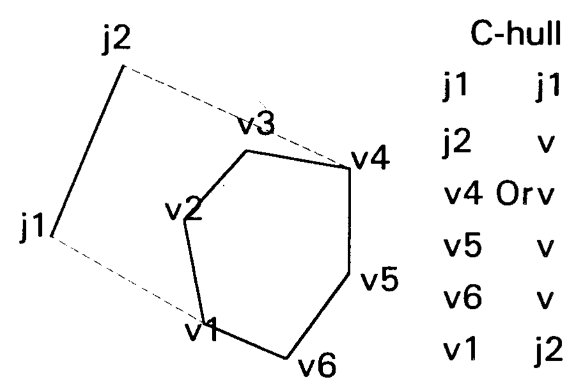

Figure 1.(a)

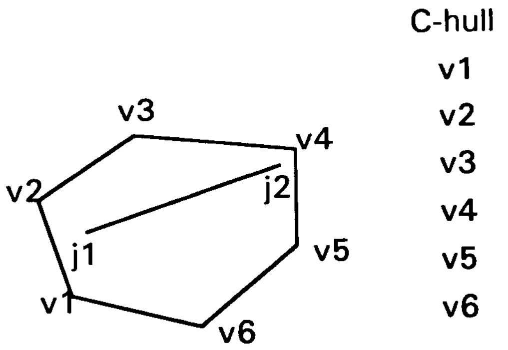

Figure 1.(b)

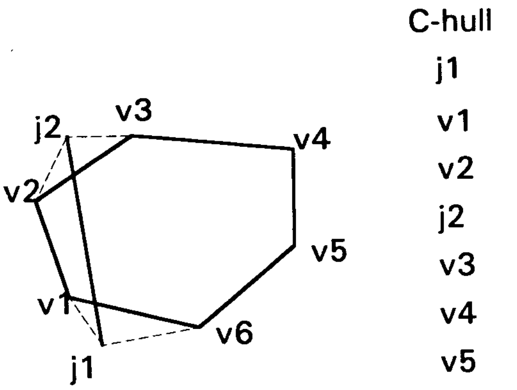

Figure 1.(c)

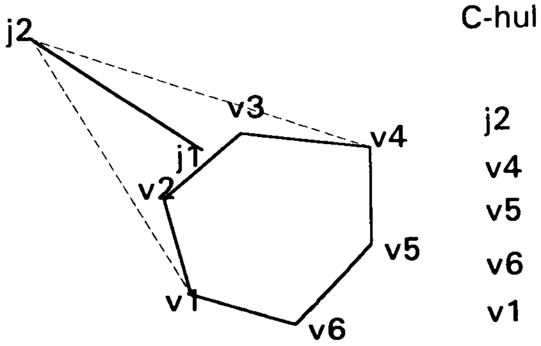

Figure 1.(d)

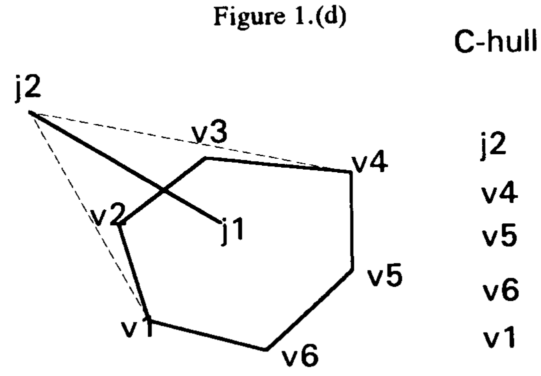

Figure 1.(e)

3. EXPERIMENTS AND RESULTS

The efficiency of the proposed method is demonstrated through three experiments carried out on a five-DOF and a seven-DOF planar manipulators (figs. 2-4). The links of the manipulators are assumed to be of the same length and equal to 50cm. Joint angles can range between -45 degrees and +225 degrees.

The proposed method was implemented in Pascal programming language and tested on an IBM-486/66 machine. The main characteristics of the proposed GA are:

Population size	30
Crossover probability	0.6
Mutation probability	0.0333
Chromosome length	10*DOF
Nnumber of generations	50
Coding	concatenated, mapped, unsigned binary
Selection method	roulette-wheel
Scaling	linear

With these assumptions, each joint angle of the robots is represented by a 10-bit string, and each such string is concatenated to produce a string representing a robot-configuration. Therefore, a 50-bit string was used for the 5-DOF robot and a 70-bit string for the 7-DOF robot.

In the first experiment (figure 2) the 5-DOF robot must place its end-effector with free orientation on specific locations corresponding to some "knot" points on a desired trajectory (a straight line parallel to X-axis) in an environment without obstacles. In this case the method use as fitness the function given by eq. (5).

The same experiment is repeated in an environment with an obstacle. Actually, the robot's motion is constrained by a rectangular obstacle. Figure 3 illustrates the results of the numerical simulation of the algorithm for this experiment. As we can see from this figure, the robot avoids the obstacle (the hatched region) and places its end-effector with an acceptable accuracy on the desired locations on the dashed line. Table 1 summarizes the Cartesian coordinates of the desired "knot" points (first two columns) and the corresponding final positional errors produced by the GA. In the third column of the table are given the positional errors for the experiment without obstacle; where in the last column are given the end-effector's positional errors for the experiment with the polygonal obstacle.

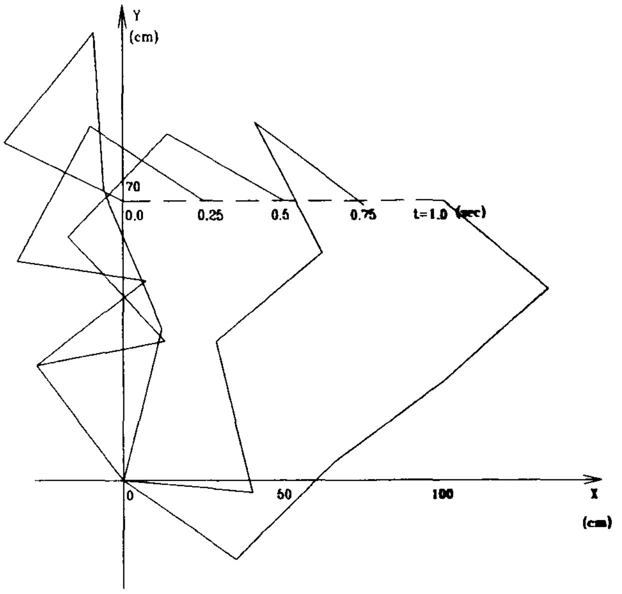

Figure 2: Simulation results for the 5-DOF robot in environment without obstacles.

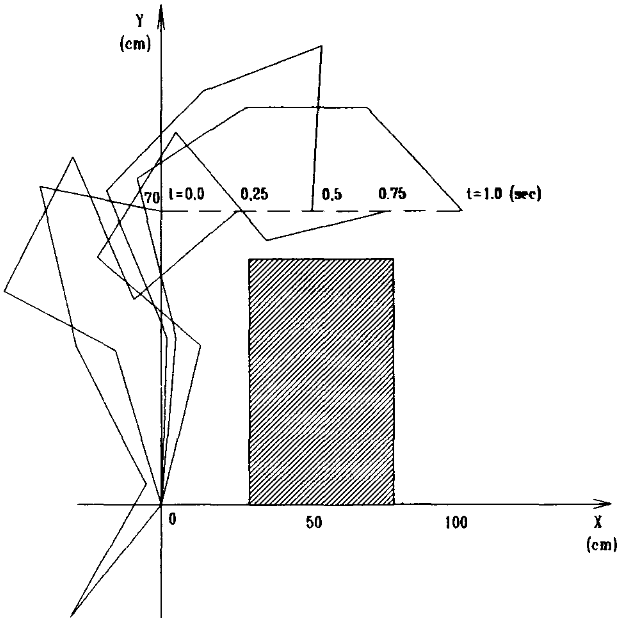

Figure 3: Simulation results for the 5-DOF robot in environment with obstacles.

A third and more complex experiment is illustrated in figure 4. In this experiment, a 7-DOF robot must work inside a narrow passage generated by two polygonal obstacles (shown by hatch lines) placing its end-effector (having free orientation) on specific desired locations. The satisfaction of the above requirements is clearly shown in figure 4 for four different robot configurations.

The fact that some of the robot's links may touch an obstacle is not a drawback of the algorithm. In any case, if one needs a minimum "clear" distance between an obstacle and the robot's body, then he or she can isotropically expand the obstacle's boundary by this distance and apply the proposed algorithm taking into account the new geometry of the obstacle.

X	Y	ErrorP (cm)	ErrorP (cm)
0	70	0,027	0,071
25	70	0,048	0,095
50	70	0,009	0,193
75	70	0,260	0,181
100	70	0,083	0,174

Table 1: End-effector's Positional errors generated by the proposed GA.

It is clear from figures 3 and 4, that the inverse kinematics solution based on the proposed algorithm is applicable and effective for obstacle avoidance problems.

The positional accuracy of the proposed algorithm is better, compared to that appeared in (Parker et al., 1989) (although obstacles avoidance is also considered), and to the results appeared in (Nakamura et al., 1987). In all the experiments the proposed obstacle avoidance scheme is quarantee. Furthermore, the proposed algorithm is very simple and easy to be used by the operator. It only needs the geometry of the robot, the obstacles' geometry, and the final desired end-effector's location, characteristics that are provided through modern CAD systems. Any other intervention of the operator like the definition of the initial (start) configuration of the robot, the definition of a reference joint angle as in (Nakamura et al., 1987), or the determination of special gain factors as in (Maciejewski and Klein, 1985), is not required.

The basic properties of the GAs have been verified in all the experiments carried out for this work. More specific, although the search space is very complex, with discontinuities and non-linearities (due to the obstacles' appearance), GAs do not fall in local optima; instead, they generally find nearly global optima. This is very important comparing to traditional optimization techniques; for example hill-climbing techniques are unsuitable for use since they get stuck in local optima. The use of potential functions in (Nakamura et al., 1987) has this disadvantage. Furthermore, they do not require any form of smoothness such as continuity of derivatives in order to work properly. This implies that "any" cost (or fitness) function can be selected for optimized. Finally, solving the inverse kinematics problem no singularities have been examined in all the experiments.

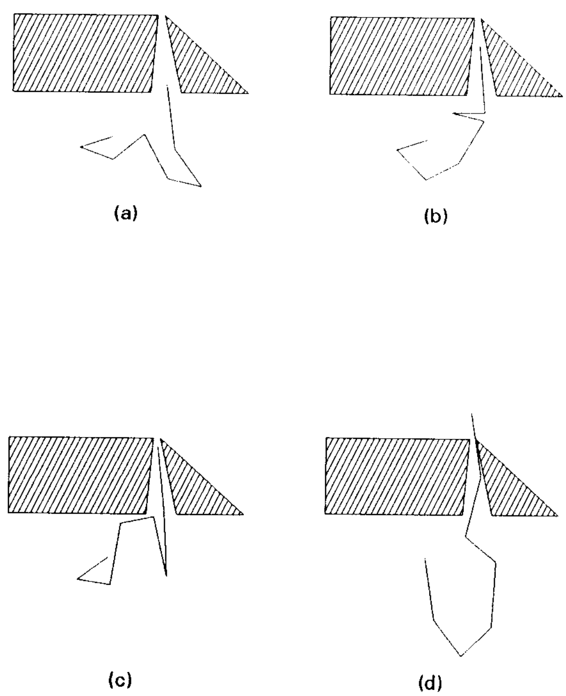

Figure 4: Motion of a 7-DOF robot inside a narrow passage.

4. CONCLUSIONS

A method based on genetic algorithms was introduced to solve the problem of inverse kinematics of redundant robot manipulators in environments with obstacles. The problem was formulated as a constrained optimization problem with main objective the minimization of the end-effector's positional error, and secondary objective the satisfaction of the constraints related to obstacle avoidance. A technique to manage constraints in the genetic search in order to maintain feasibility was also presented. The efficiency of the proposed algorithm was demonstrated through three experiments carried out on two robots with five and seven-DOF, respectively. The algorithm quarantees the collision-free movement of the robot producing an acceptable positional error. It must be underlined that with an appropriate expression of constraints related to obstacles the proposed algorithm can be also applied in 3-D problems. Actually, any scheme expressing the 3-D constraints like distance functions can be incorporated into the GA. It is worthwhile to investigate such a scheme in a future work.

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