CHAPTER 1

INTRODUCTION AND LITERATURE SURVEY

1.1 INTRODUCTION TO ROBOT INVERSE KINEMATICS

Robotic manipulator kinematics deals with the analytical study of the geometry of motion of a robotic manipulator with respect to a fixed reference coordinate system as a function of time without regard to the forces and moments that cause the motion. In particular, it provides a mapping between the joint variables and the position and orientation of the end-effector of a robotic manipulator.

Computer-based robots are usually controlled in the joint variable space in which the configuration of the manipulator is described by a vector whose components are the values associated with each joint variable with respect to some calibration point. The most natural coordinate system for human beings is the standard Cartesian system and the path of the object to be manipulated by the robot end-effector is usually expressed in the Cartesian space. The joint variable determination for accomplishing a given task is, therefore, indispensable for the control of an industrial robot. The inverse kinematics determines the joint variables that would result in a desired position and orientation of the end-effector of the robotic manipulator with respect to a reference coordinate system.

The inverse kinematics solution of non-redundant robots is difficult since the mapping between the joint
variables in the joint space and the robot end-effector position and orientation in the Cartesian space is non-linear. Further, this mapping involves transcendental equations having multiple solutions (Craig, 1989). The number of multiple solutions depends upon the number of joints in the manipulator, the link parameters and the allowable range of motion of the joints. For an industrial robot having intersecting last three axes, the solution of the wrist positioning and hand orienting joint variables can be decoupled (Pieper, 1968). A SCARA robot has two multiple solutions whereas a PUMA robot has four multiple solutions that achieve the same position of the robot wrist. There may be certain points in the workspace of these robots where the number of available multiple solutions is less than the above mentioned numbers due to the allowable range of motion of the joints.

A single solution out of the multiple available solutions has to be subsequently chosen. This process of obtaining a unique solution can be referred to as a multiplicity resolution. Obstacles are defined as any object in the robot workspace with which contact of the robotic manipulator is undesirable. In the absence of obstacles, the robot configuration closest to the current robot configuration in the wrist positioning joint space may be selected. An approach which evaluates all the possible multiple inverse kinematics solutions of the robotic manipulator and subsequently achieves a multiplicity resolution for effecting actual robot motion is therefore desired. In case the approach is to be used for off-line calculations, the computational effort of the approach can be ignored.

Industrial robotic applications involving point-to-point motion may involve work environments having
stationary obstacles. Kinematic redundancy becomes desirable as industry demands more versatile and dexterous manipulators for such robotics applications. There exist certain tasks for which even a non-redundant industrial robot may be considered redundant. Thus the motion of manipulators that are not normally considered redundant may be optimized (Anderson and Angeles, 1989). For example, a non-redundant robotic manipulator may be required to position its end-effector without any specific orientation at the 'knot points' of its path. At these knot points, the robotic manipulator has more than three degrees of freedom for positioning its end-effector and exhibits kinematic redundancy.

The introduction of kinematic redundancy further complicates the kinematic inversion. For a redundant manipulator there are infinite number of joint coordinate vectors that correspond to the same end-effector position. This is due to the fact that the number of degrees of freedom of the manipulator is greater than the dimensions of the workspace. The additional degrees of freedom of redundant manipulators can be utilized to give the robot extra capabilities, hereafter referred to as performance criteria, which include the ability to minimize total joint displacement and avoid external obstacles while operating in the entire workspace. A unique solution may be found if these performance criteria are imposed on the manipulator kinematics, known as a redundancy resolution.

1.2 LITERATURE SURVEY

Paul (1981) proposed the use of homogeneous transformation matrices to obtain the inverse kinematics solution of non-redundant robots. The solution was obtained in a sequential manner, isolating each joint
variable by pre-multiplication by a number of homogeneous transforms in each equation. Multiple solutions for an elbow manipulator corresponding to ‘elbow up’ and ‘elbow down’ configurations were obtained trigonometrically. The issue of multiplicity resolution has not been addressed by the author. Moreover, geometric intuition has been suggested at certain points of the solution for certain manipulators.

Details of research work done in the area of obtaining the inverse kinematics solution of industrial non-redundant robots can be found in the robotics book by Fu et al. (1987). Fu et al. (1987) have presented the inverse transform technique of determining the joint solution of a manipulator. This technique is based on the paper by Paul et al. (1981). The technique does not give a clear indication of how to select an appropriate solution from the several possible inverse kinematics solutions for achieving a particular goal position. The user often needs to rely on his or her intuition to pick the right answer. A geometric approach based on the work of Lee and Ziegler (1984) has also been presented in Fu et al. (1987). The discussion focuses on a PUMA-like manipulator. A position vector pointing from the shoulder to the wrist of the robot is first derived. This is used to derive the solution of each joint $i(i=1,2,3)$ by looking at the projection of the position vector onto the link coordinate $x_{i-1}-y_{i-1}$ plane. The last three joints are solved using the calculated joint solutions for the first three joints and the projection of the link coordinate frames onto the $x_{i-1}-y_{i-1}$ plane. This approach utilizes arm configuration indicators which have to be pre-specified by a user for finding a particular configuration out of the multiple configurations available from the inverse
Moreover, the approach utilizes geometric heuristics to take advantage of the special structure of the manipulator.

Ozgoren (2002) thoroughly investigated non-redundant six-joint serial manipulators from the viewpoint of their inverse kinematics solutions. To do this systematically, the manipulators were classified according to their joint arrangements and two topological concepts were introduced as type number and conjugacy. The conditions of validity were stated and the valid manipulators were further classified into four groups according to their type numbers. The concept of conjugacy lead to a reduction in the number of manipulators to be investigated. The minimal conditions for the existence of analytical solutions were determined. The ways of obtaining analytical solutions were described for all typical samples of joint arrangement and type number classifications. If analytical solutions did not exist, then it was described how to obtain semi-analytical solutions of first, second, or at most third order. A $k^{th}$ order semi-analytical solution was defined as one in which the number of equations to be solved numerically can be reduced to $k$. Simplifications and manipulations of the kinematics equations both for their analytical or semi-analytical solutions and for the topological analysis of manipulators were achieved by means of the numerous properties of the exponential rotation matrices. However, the issues of multiple solutions and multiplicity resolution have not been addressed in this paper.

Uicker et al. (1964) and Milenkovic and Huang (1983) presented iterative solutions for most industrial robots. However, there is no indication as to how to choose the
correct solution for a particular arm configuration as in the inverse transform technique of Paul et al. (1981).

Numerical solutions to the inverse kinematics problem of non-redundant manipulators have been reported by Angeles (1985) and Angeles et al. (1988). The issues of multiple solutions of the inverse kinematics problem and multiplicity resolution, however, have not been addressed by the authors.

A numerical technique based on a successive linear approximation principle (Griffith and Stewart, 1961) has been proposed by Jain and Sharan (1990). Though this technique can also be applied to redundant manipulators, it does not provide the multiple solutions of the inverse kinematics problem. It only calculates the single solution of the inverse kinematics problem that requires minimum movement of the robot joints.

Neural network approaches to the solution of the inverse kinematics problem have been reported by Guez (1988), Tawel et al. (1988), Arteaga-Bravo (1990) and Hornik (1991). The major limitations of the implementations are the relative poor precision of the outputs compared to the conventional algebraic or numerical solutions and the inability of the models to provide the multiple solutions of a robotic manipulator.

A structured artificial neural-network (ANN) approach has been proposed by Karlik and Aydin (2000) to solve the inverse kinematics problem of a robot manipulator. The learning equations used are those of the backpropagation algorithm (Haykin, 2001). In this work the solution of the inverse kinematics problem of a six-degree-of-freedom robot manipulator is implemented by using ANN. Work has been undertaken to find the best ANN configuration for this
Two ANN configurations having different number of neuron layers and number of output neurons are proposed. Both the placement and orientation angles of a robot manipulator are evaluated through the ANN outputs. The precision of the outputs needs to be improved and the multiple inverse kinematics solutions of the robotic manipulator are not provided by the approach.

A modular neural network architecture has been proposed by Oyama et al. (2001) to provide the inverse kinematics solution of a robotic arm. The effectiveness of the proposed approach for the inverse kinematics model learning has been illustrated through simulation experiments. The complexity of the computation procedure and the non-inclusion of multiplicity resolution are the major limitations of the proposed architecture.

A neuro-genetic approach to obtain the inverse kinematics solution of a robotic manipulator has been reported by Kalra and Prakash (2003). A multi-layered feed forward neural network architecture was used. The weights of the neural network were obtained during the training phase using a real-coded genetic algorithm. This training algorithm does not suffer from the usual drawbacks of the backpropagation learning algorithm (Haykin, 2001) which gets stuck up in local optima. The network response was compared with the desired response and the relative errors of the joint variables were evaluated for different points in the manipulator workspace. The relative errors were small establishing the validity of the proposed approach. However, the approach was applied to obtain the inverse kinematics solution of a planar manipulator and can thus be applied to SCARA industrial robots. The efficiency of the method to solve the inverse kinematics problem of a
non-planar industrial robotic manipulator needs to be investigated.

Ivlev and Graser (1997) have obtained the solution for the inverse kinematics of redundant robots through the addition of imaginary links, which limit and adapt the robots flexibility to an actual workspace or end-effector motion. The inverse kinematics solution is obtained in a closed form. The technique is illustrated for two planar manipulators. However, its extension to a spatial robot is not presented. Moreover, the technique involves the selection of an anchor point and a robot joint between which an imaginary robot link is connected. The selection of different imaginary robot links results in different poses of the robot and the choice of a pose corresponding to minimum total joint displacement cannot be made.

Goldenberg et al. (1985) introduced a generalized solution for the inverse kinematics of robots. Their method uses the modified Newton-Raphson technique for solving the system of non-linear kinematics equations regardless of whether the robot is redundant or non-redundant. Their procedure is fairly robust and can be used for a variety of robots. The major shortcoming of their method is that the convergence of the solution to the desired point depends upon the quality of an initial guess. As a result, the convergence of the technique cannot be guaranteed.

The problem of collision avoidance of a redundant manipulator with an obstacle in its workspace has been studied by Mitsi and Bouzakis (1993). The proposed method is based on simulating the redundant manipulator and the obstacle with convex volumes. The number of convex volumes (spheres) as well as their characteristic parameters, e.g. radius and center, are determined with respect to the
required accuracy of simulation. The relative position of the manipulator links are described by using the Denavit-Hartenberg homogeneous transformation matrices (Fu et al., 1987). The kinematics equations are developed using the Lagrange multiplier method and the criterion of obstacle avoidance is taken into account. The solution of the inverse kinematics has been obtained by a numerical method. The results obtained are checked by graphical simulation of the manipulator motion. The increased kinematics dexterity of a redundant manipulator can thus be utilized and the use of sophisticated jigs and fixtures in manufacturing and assembly environments can be avoided. However, additional performance criterion like total joint displacement minimization has not been included in the analysis.

The inverse kinematics problem of a spatial redundant or non-redundant manipulator taking into account criteria like collision avoidance and the limits of joint motion has been solved by Mitsi et al. (1995). A simulation manipulator-obstacle model created with convex volumes is used to achieve collision avoidance. The solution of the inverse kinematics has been obtained by the penalty function method. The developed procedure has been tested by solving a spatial manipulator with five revolute joints. The results are used for the off-line programming of this manipulator which is used in a work station for various manufacturing processes. The results obtained have been checked by graphical simulation of the manipulator motion and guarantee, for a prescribed position and orientation of the end-effector, a collision avoidance respecting the joint limits. However, additional performance criterion like total joint displacement minimization has again not been included.
Many inverse kinematics schemes resolve redundancy at the velocity level and are termed velocity-based resolution schemes. The most popular resolution scheme with an obstacle avoidance capability is based on the inversion of the Jacobian matrix. The idea is to use 'self-motion' to avoid obstacles. Nakamura et al. (1987) considered a task priority-based scheme in which the task for a redundant manipulator was broken down into two sub-tasks with decreasing order of priority. The approach first satisfied the primary sub-task and used the redundancy to best match the secondary sub-task. The secondary subtask was to be chosen by the operator so that all the manipulator links remained away from obstacles. While it may be intuitive to choose the secondary subtask to avoid obstacles in a simple environment, the choice may be difficult for a complicated environment with many obstacles. Hence, the usefulness of this approach is limited.

Another obstacle avoidance approach was suggested by Maciejewski and Klein (1985). They identified for each period in time a point on the manipulator that was closest to an obstacle, termed the obstacle avoidance point, and assigned to it a desired velocity component in a direction that was directly opposite to the surface of the obstacle. Their method works well in an environment with relatively few obstacles and having large free space. In a cluttered environment, the location of the obstacle avoidance point and its velocity are crucial for the success of this method, but there is no systematic way of choosing them. In addition, even if the velocity of the obstacle avoidance point is specified, avoidance of obstacles cannot be guaranteed for all the links.

Cheng et al. (1993) proposed a quadratic programming method for obstacle avoidance. Their idea uses the concept
of obstacle avoidance point proposed by Maciejewski and Klein (1985) and provides an alternative way of solving the equations. Instead of specifying the velocity equation for the obstacle avoidance point as an explicit constraint, Cheng et al. (1993) formulated the obstacle avoidance problem as an optimization problem with the velocity equation for the obstacle avoidance point being the objective function to be minimized. The desired end-effector motion was specified as an equality constraint with additional inequality constraints on maximum deviation in joint space. This approach also suffers from the shortcomings of the approach of Maciejewski and Klein (1985).

Sezgin et al. (1997) handled obstacles for a planar robot using the idea of the Voronoi diagram. Points on the manipulator, known as configuration control points (CCPs), were chosen. Similarly selected control points on the Voronoi diagram were also chosen. The objective function was defined as the sum of distances between CCPs and the control points on the Voronoi diagram. The joint configurations of the robot were obtained by minimizing the objective function. However, the selection of CCPs is very difficult, and the wrong choice can result in collision with obstacles. In addition, this approach is easily applicable only to two-dimensional planar manipulators as the Voronoi diagram for a three-dimensional environment is difficult to construct.

Approaches which achieve obstacle avoidance through redundancy resolution at the joint velocity level have also been presented by Baillieul (1986), Chen and Vidyasagar (1988), Chevallereau and Khalil (1988), Klein and Chirco (1987) and Walker and Marcus (1988). Approaches, which resolve the redundancy in the presence of obstacles
at joint velocity level, do not provide the joint position for a given location of the end-effector. They also suffer from the natural drift phenomenon of pseudoinverse control (Klein and Kee, 1989).

A new redundancy resolution approach for manipulators at the joint position level has been proposed by Ding et al. (2000). The proposed approach is based on the idea of maximizing the shortest distance between the link-obstacle pairs. Algorithms for evaluating the Euclidean distance between two convex polytopes have been suggested by Gilbert et al. (1988), Gilbert and Foo (1990), Lin and Canny (1991), Hurteau and Stewart (1988) and Bobrow (1989). Ding et al. (2000) have used the algorithm of Gilbert and Foo (1990) in their work. Numerical experiments in both two and three dimensional spaces show the viability of the proposed method. Constraints on the joint angle values and additional performance criterion like total joint displacement minimization have however not been included.

The approach of Lozano-Perez and Wesley (1979) and Lozano-Perez (1983) for collision avoidance is based on the characterisation of the position and orientation of a robot as a single point in its configuration space. Geometric objects called configuration-space obstacles are constructed and a path from the initial configuration to the final configuration is subsequently established. These algorithms have the advantage that the intersection of a point relative to a set of objects is easier to deal with than the intersection of objects among themselves.

Collision avoidance in the configuration space has been achieved through the visibility graph approach by Nilsson (1969) and Mitchell (1988). The vertices of the
undirected graph are the initial and goal configuration of
the robot and the vertices of the C-obstacles. O'Dunlaing et al (1983) and O'Dunlaing and Yap (1985) use
the retraction method in the configuration space to accomplish obstacle avoidance. The method uses a Voronoi
diagram whose edges represent paths that are equidistant from the closest pair of obstacles and vertices are points
where three or more such paths meet. Collision avoidance in
the configuration space using the freeway method has been
reported by Brooks (1983).

The disadvantage of the configuration space approach
is that the construction of the configuration space
obstacles for articulate robots, that is, the required
mapping of the physical objects into the robot's
configuration space is a difficult and time-consuming task
as shown by Hwang (1990), Ge and McCarthy (1990) and Dooley

Khatib (1986) introduced the potential field approach.
This approach treats the robot as a point moving in its
C-space under the influence of an artificial potential
field produced by the final desired configuration and the
configuration space obstacles. Here the final configuration
produces an attractive potential which pushes the robot
Towards its goal and the configuration space obstacles
generate a repulsive potential which pushes the robot away
from them. The negative gradient of the summation of these
potentials is treated as an artificial force applied to the
robot to control its motion. This approach suffers from the
disadvantage of the configuration space approach mentioned
above. Moreover, the potential field approach for
optimizing the artificial potential function may get stuck
in local optima.
Evolutionary algorithms mimic natural evolutionary principles to constitute search and optimization procedures. The most popular evolutionary algorithm is the genetic algorithm (GA). GAs work with a population of solutions, instead of one solution at each iteration. They have two distinct operations, namely selection and search (Coley, 2001). In the selection operation, better solutions in the current population are emphasized by duplicating them in the mating pool. In the search operation, new solutions are created by exchanging partial information among solutions of the mating pool and by perturbing them in their neighbourhood. GAs do not use any gradient information during the above two operations. In addition, their representations are flexible. These properties make them flexible enough to be used in a wide variety of problem domains.

Shibata and Fukuda (1993) and Shing and Parker (1993) have proposed genetic algorithms to obtain a collision-free path assuming a predefined map consisting of knot points. Lin et al. (1994) proposed an evolutionary algorithm for a collision-free path generation in a mobile robot environment which may contain unknown obstacles. The main characteristic of the above genetic approaches is that they pre-suppose the representation of the robot as a single point, moving among its configuration space obstacles. Therefore, it is difficult to apply them on articulate robotic manipulators.

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. The issue of obstacle avoidance has not been addressed in this paper.

Nearchou and Aspragathos (1996) proposed a new task oriented solution to the inverse kinematics problem of redundant robot manipulators in relation to obstacle avoidance. The problem was 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 to provide robust search in complex spaces with discontinuities (Goldberg, 1989). They are able to reach a global optimal solution in a complex search space which can be multimodal and non-linear. Constraints related to obstacles in the robot's environment require the search of such complex spaces. Furthermore, by using GAs there is no need to compute the Jacobian matrix, so that any problem related to the inversion of this matrix is overcome. In the proposed method only the forward kinematics equations of the robot are used which are simple to develop. However, the proposed obstacle avoidance algorithm is valid only for planar manipulators operating in an environment with convex obstacles.

Nearchou (1998) suggested an evolutionary approach based on a modified binary-coded genetic algorithm (GA) to obtain a unique solution for the inverse kinematics problem of non-redundant industrial robots and redundant robots. The issue of multiplicity resolution of an industrial PUMA robot was solved through the minimization of total joint displacement. The closest solution in the joint space relative to the current configuration was evaluated. The superiority of the evolutionary approach over the well-known pseudo-inverse method and the simple binary-coded genetic algorithm has been established in the
work. However, the proposed approach suffers from certain limitations. A two level binary-coded GA is proposed wherein potential solutions are evaluated by the high level GA and incremental changes are evaluated by the low level GA until a global optimum is achieved. It has been shown by Deb and Agrawal (1995) that real-coded GAs are more suitable for continuous search spaces compared to binary-coded genetic algorithms. Moreover, the multiple configurations of an industrial robot existing due to the multimodal nature of the inverse kinematics problem are not available at the end of the search since only the best solution based on the minimization of total joint displacement is evaluated.

Nearchou and Aspragathos (1997) used a genetic algorithm to achieve collision avoidance during pick and place tasks in a work environment having obstacles. Multiple simulation experiments were carried out on several robots. However, the simulation experiment on the spatial robot assumes that the links of the robot are cylinders of zero radii, that is, they are treated as lines. This assumption is unrealistic for an actual robotic manipulator.

1.3 OBJECTIVES OF CURRENT WORK

Keeping in view the work done by various researchers mentioned above, the following objectives are addressed in the current work:–

1. Use an evolutionary approach based on a real-coded genetic algorithm to solve the inverse kinematics problem of non-redundant robotic manipulators. The approach should provide the multiple solutions of the robotic manipulator considering the restrictions imposed by the joint limits.
2. Graphically display the multiple configurations obtained in objective 1 for ease of visualization of the available multiple solutions.

3. Use an evolutionary approach based on an elitist real-coded genetic algorithm to solve the inverse kinematics problem of redundant robotic manipulators. Performance criterion like total joint displacement minimization would be included to achieve a redundancy resolution.

4. Incorporate an obstacle avoidance algorithm into the evolutionary approach for the inverse kinematics solution of redundant robots.

1.4 ORGANIZATION OF THESIS

The current research work in the area of solving the inverse kinematics problem of a robot has been carried out along the following lines:-

i) The inverse kinematics problem of a non-redundant robotic manipulator involves the solution of non-linear equations having transcendental functions. These equations have multiple solutions. The number of solutions depends upon the number of joints in the manipulator, the link parameters and the allowable range of motion of the joints. As seen in the literature review, earlier reported methodologies either use geometric intuition at certain points of the solution for certain manipulators or utilize geometric heuristics to take advantage of the special structure of the manipulator or do not provide the multiple solutions. An evolutionary approach based on a real-coded genetic algorithm can provide multiple
solutions of the inverse kinematics problem. The suitability of a real-coded genetic algorithm over a binary-coded genetic algorithm for obtaining the inverse kinematics solution is discussed in Chapter 2. The mechanics of a real-coded genetic algorithm are then described. The steps of the algorithm, that is, initialization, evaluation and selection, recombination and mutation are presented.

ii) The kinematic modelling of a robot and the formulation of the inverse kinematics problem as an optimization problem for non-redundant wrist-partitioned robots is carried out in Chapter 3. The solution of this optimization problem evaluates the multiple configurations of the robot for a particular position and orientation of its end-effector. The parameters of the real-coded genetic algorithm for the specific problem are defined. Two niching strategies for the tournament selection operator, along with the simulated binary crossover operator and a parameter-based mutation operator, are used independently to carry out the multimodal optimization. A 3D robot modeller is developed in MATLAB for providing a graphic display of the multiple configurations of the robot. This modeller synthesizes the robot links using geometric data which is defined in the local coordinate frame of the links. The robot links are displayed in their appropriate global locations through the use of DH parameters. The evaluation of the multiple configurations and their subsequent visualization through the 3D modeller are illustrated through
Simulation experiments carried out on a SCARA and a PUMA manipulator. The advantages of the proposed approach over the existing approaches are brought out using these simulation experiments.

iii) The inverse kinematics solution of a redundant robot manipulator is carried out in Chapter 4. Redundancy resolution is achieved through the performance criterion of total joint displacement minimization. The formulation of the inverse kinematics problem of a redundant robot as an optimization problem is carried out. An obstacle avoidance algorithm based on spherization of the robot and the obstacles is incorporated into the solution scheme. The parameters of the real-coded genetic algorithm for the specific problem are defined. Simulation experiments to illustrate the efficacy of the approach are carried out on a Mitsubishi Movemaster RV-M1 robot. This robot is normally considered as non-redundant. However, as mentioned in Section 1.1, it can be considered redundant in certain specific situations where its end-effector has to be positioned at a particular location with no particular orientation.

iv) Finally, in Chapter 5, the conclusions have been drawn and suggestions for future work have been given.