Chapter 8: Conclusion

This dissertation introduced generalized inverse kinematics for serial robots. The development of the direct search inverse kinematics method is the most important contribution of this work. The direct search inverse kinematics method is valid for all serial robots and allows for the incorporation of an unlimited number of performance criteria. The direct search method also has the important quality that it converges at singularities. Direct search addresses the generalized inverse kinematics problem as a decision making problem with an unlimited number of performance criteria, equality constraints and inequality constraints. The direct search seeks to optimize the performance criteria while simultaneously satisfying the constraints. Another important contribution of this work is the design and implementation of an automatic plant description system. The direct search inverse kinematics algorithm uses the automatic plant description system to generate performance criteria values during the course of the solution. The automatic plant description system is also useful for robot design, robot selection, and the configuration of modular robots in response to task requirements. Direct search was tested in simulation for a wide variety of robots and was tested experimentally on a modern research robot with seven degrees of freedom. Finally, this dissertation included a road map that discussed the future of generalized inverse kinematics in the context of ten advanced applications for robots and ten crucial supporting technologies.

Direct search is a method of solving problems numerically using sets of trial solutions to guide a search. The direct search inverse kinematics method begins at an estimate of the solution. This estimate serves as an initial base point for the search. A pattern of explorations about the base point generates a set of trial solutions. A decision making process evaluates the trial solutions and chooses one as the next base point for the search. The search generates another pattern of perturbations about this new base point and again chooses one as the next base point. This process of local exploration and decision making continues until the search converges to a solution.

The direct search inverse kinematics method is general with respect to the robot's geometry. The exploration and decision making processes do not require geometric or algebraic simplifications particular to any given robot. The direct search method may be applied to any robot with any number of degrees of freedom.

The direct search method allows for the incorporation of an unlimited number of performance criteria. Each trial solution completely determines the state of the robot. This allows all performance criteria, equality constraints, and inequality constraints to be explicitly calculated and used during the decision making process.

Direct search's ability to converge at singularities is unique among inverse kinematics methods. Because all robots have singularities, this is an extremely important quality. Direct search converges at singularities because generating trial solutions and making decisions does not require any scalar or matrix inversion.

Direct search addresses the generalized inverse kinematics problem as a decision making problem with an unlimited number of performance criteria, equality constraints, and inequality constraints. The criteria and constraints must be functions of the joint displacements and/or their time derivatives only. The direct search method does not constrain the definition of optimality. The multicriteria inverse kinematics chapter discusses two definitions of optimality. The first is a non-dominated solution and the second is a minimum of a composite performance index.

The performance criteria are employed when choosing an optimum form among the set of trial solutions. These criteria may be dependent or independent of one another. Performance criteria independent of one another may give conflicting information as to the optimum solution. Dependent performance criteria lead to “double-counting of their shared effects. These complications are simply some of the realities of the generalized inverse kinematics problem.

The equality constraints represent the heart of the inverse kinematics problem. The fundamental equality constraints are the position and orientation constraints on the placement of the end-effector. Solving for the joint displacements given these equality constraints is the inverse kinematics problem. There may also be equality constraints on the higher order properties of the end-effector state.

Inequality constraints typically become important during the operation of an actual robot. The physical travel limits on the joint displacements (joint limits) are examples of equality constraints. All robot actuators have a finite maximum speed which represents another inequality constraint. The actual joint speeds must be less than or equal to the maximum speed of the actuators. Acceleration, torque, and force limits are all examples of inequality constraints.

A non-dominated solution is one method of defining optimality. A non-dominated solution is superior to all other solutions with respect to at least one criteria and at least as good with respect to all the remaining criteria. The main benefit of this definition of optimality is that scaling difficulties are essentially eliminated. There is no summing of effects and no mixing of units, though the criteria may be ranked relative to one another. This allows the operator some control over the ultimate solution. Once the criteria are ranked, however, an extremely simple rule determines the choice of an optimum solution.

A minimum of a composite performance index is the other definition of optimality this dissertation considered. A composite performance index is essentially a weighted sum of all the criteria values. In summing the effects of different criteria, scaling issues are paramount. This dissertation develops scaling procedures in the context of direct search that produce criteria values of comparable value. This scaling procedure draws on previous work in the area of criteria normalization (Bevill and Tesar, 1990). A procedure for transforming both equality and inequality constraints and expressing them as performance criteria was also developed.

Sequential filters, originally developed for mechanism synthesis, were combined with direct search to form a powerful generalized inverse kinematics method. Sequential filters sorts and ranks the trial solutions to reduce the number of choices presented to the decision making process. The addition of sequential filters both increases the solution speed and eliminates problems associated with extraneous minimum. Most importantly, sequential filters allow the robot's operator to stay "in the loop" and influence the course of the solution.

Another important contribution of this doctoral work is the design and implementation of an automatic plant description system. The plant description is essentially a dynamic model of the robot. In its current form, this plant description system calculates performance criteria values, the joint forces or torques, and the deflection of the robot's end-effector. The system is automatic because it produces its numerical outputs given its parametric inputs without further user intervention. The direct search inverse kinematics algorithm uses the automatic plant description system to generate performance criteria values during the course of the solution. The automatic plant description system is also useful for robot design, robot selection, and the configuration of modular robots in response to task requirements.

The design began by identifying the system's inputs and outputs. The inputs are: the externally applied loads, a joint-level description of the robot's path, and a description of the robot. The outputs are: the robot's geometry and other pertinent parameters, the joint torques and forces, the end-effector deflection, and the criteria values. The inputs and outputs determined a set of specifications for the system. To meet these specifications, the design process divided the plant description system into three subsystems: formulation, calculation, and database.

The calculation subsystem is where several of the outputs of the automatic plant description system are actually generated. The input to this system is a parametric description of the robot and the task that the robot is to perform. The outputs are the joint torques or forces, the end-effector deflections, and performance criteria values. This subsystem could reside on a general-purpose computer for simulation applications, or it could reside on a specialized computer for real-time control applications. The important issue is the identification and description of the subsystem's inputs. The proper inputs can then be communicated to the calculation subsystem wherever it resides. There are two general types of inputs. The robot-specific inputs describe the robot's physical parameters and the task-specific inputs describe the task.

The automatic plant description system's database keeps a record of the available modules and associates with each module a variety of information. The modeling subsystem accesses the database and gathers the information required by the calculation subsystem. Other processes may access the database as well. For instance, the automatic configuration of a modular robot in response to task requirements requires information about the available modules. The design process identified four different types of databases: list, hierarchical, relational, and object-oriented. The list database was chosen for the implementation because it matched the requirements of the automatic plant description system and could be written entirely "in-house".

The model formulation subsystem is the heart of the automatic plant description system. This subsystem's input is a description of the robot. This description may be of either a modular or monolithic robot. Using the robot's description and information in the database, this subsystem assembles the parameters and formulates a model of the robot. The model of the robot is generated and transferred to the calculation subsystem for analysis. The model must be expressed in either a modular or Denavit and Hartenberg format depending upon the analysis software. There are four combinations of input and output formats: a modular robot with module-based analysis, a modular robot with Denavit and Hartenberg-based analysis, a monolithic robot with module-based analysis, and a monolithic robot with Denavit and Hartenberg-based analysis. A procedure for extracting Denavit and Hartenberg parameters from a modular robot description was the major development during the design of this subsystem.

An example of the automatic plant description system was presented for a modular robot with seven degrees of freedom. The example shows the steps presented to the user and the necessary input parameters. The example shows the system's outputs using representative plots and gives run times on an inexpensive personal workstation and on a specialized array processor.

Experimentation and simulation verified the effectiveness of the direct search inverse kinematics method. Several different robots having especially difficult or interesting geometries were tested. The robots cover a spectrum, from the industrial variety with six degrees of freedom to a conceptual hyper-redundant robot with twenty-one degrees of freedom. The examples include a graph showing the solution's accuracy and timing results for the solution speed. In each case direct search was successful in finding solutions to the required level of accuracy. One of the examples showed that the search was successful even though the robot was forced to pass through a singularity.

For the optimal direct search strategies with completely general formulations, the direct search method was about ten times too slow for real-time application. The sub-optimal search strategy with a general formulation was, however, fast enough for real-time application. Geometric simplification in the form of a spherical wrist also increased the solution speed enough for real-time application. These simplifications are solely for the purpose of increasing the solution speed and will not be necessary as computers become more powerful in the next few years.

For every researcher who has seriously worked on the inverse kinematics problem, there is probably a different solution method. Now there is one more, direct search. The goal for this doctoral work – inverse kinematics general with respect to both the robot's geometry and performance criteria – very much determined the choice of direct search. The direct search method achieves this goal of generality by formulating the exploration procedure for a general serial robot and considering any number or variety of performance criteria in the decision making strategy.

This dissertation has discussed the benefits associated with generality, but what are the costs? With computer software, the cost of generality is almost always decreased solution speed. Just as a race car is faster than a family sedan, specialized computer software is faster than its generalized counterpart. This is not to say that direct search is a family sedan. It's more like an armored tank, impervious to changing geometries and varied criteria.

The important issue is the effect this sacrifice in solution speed has on the intended applications of the direct search inverse kinematics method. For the off-line applications; robot design, monolithic robot selection, modular robot configuration, and general simulation; direct search is already fast enough. The problem is with real-time application. For the suboptimal search strategies, the solution speed is probably fast enough. Section 6.4 presented simulation results showing that geometric simplification will also increase the solution speed enough for real-time application. Geometric simplification sacrifices the generality of direct search with respect to the robot's geometry. For most applications this sacrifice is not too great. The simplification is particular to the robot and the direct search remains general with respect to the performance criteria. Thus the direct search will still optimize different criteria to enhance the robot's performance in a variety of tasks. Reconfigurable robots and fault-tolerant robots are the applications absolutely requiring inverse kinematics general with respect to the robot's geometry. For these two applications, an optimal direct search algorithm in real-time is still several years into the future.

This doctoral work began with generality. The general solution methods it developed are easily specialized to give increased solution speed for a particular robot. If the work had begun in search of a specialized solution, one likely would have been found.