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One objective of this research was to study the factors which influence the design of robot arms and wrists (configuration synthesis). Another objective was to develop efficient computational software tools for the manipulation of industrial robots. These software tools were to address the critical problems which arise in smooth trajectory planning, inverse kinematics of general robots, dynamic control of realistic robots, and parameter identification and compensation.

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# Configuration Synthesis and Efficient Motion Programming of Robot Manipulators

Final Report

by

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U. S. Army Research Office

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## Objectives

One objective of this research was to study the factors which influence the design of robot arms and wrists (configuration synthesis). Another objective was to develop efficient computational software tools for the manipulation of industrial robots. These software tools were to address the critical problems which arise in smooth trajectory planning, inverse kinematics of general robots, dynamic control of realistic robots, and parameter identification and compensation.

## Summary of Results

An extensive patent search was conducted for the geared robot wrist designs. Such wrists use remote motors for joint actuation and are compact when compared with simple serial designs with joint mounted motors. Many variations of geared wrists with orthogonal and oblique joint axes were found. The tabulation method outlined in [Gupta 85-*ASME JMTAD* 107:142-143] was explored more fully and applied to such wrist designs in [Ma 88-*MS Thesis*][Ma and Gupta 89-*JRS* 6(5):506-520]. Wrists with oblique, co-intersecting joint axes have a continuous 3-roll property. Another wrist configuration with continuous 3-roll property was analyzed in [Gupta 88-*IEEE JR&A* 4(4):440-443].

The first order differential analysis of the manipulator is a basic step in robot dynamics and control. The velocity Jacobian of the manipulator plays a critical role in this analysis. This Jacobian can be defined with respect to various end-effector points and link coordinate systems. A simple method to derive the velocity Jacobian by utilizing a new velocity-similarity principle for the 4x4 velocity matrices was presented in [Ma 88-*MS Thesis*][Gupta and Ma 90-*Robotica* 8:81-84].

When a set of discrete stations are specified along a robot task path, it becomes necessary to find a related smooth trajectory either at joint level or at end-effector level. The usual approach for this problem of trajectory planning is to fit piecewise-smooth polynomial functions. A different approach which was developed in [Mirman 87-*MS Thesis*][Mirman and Gupta 87-*JRS* 4(5):605-617] is as follows. Suppose that a trajectory is available which is not sufficiently smooth--in the simplest case, it could be piecewise-linear. A convolution smoothing process was developed which yielded a succession of related smooth trajectories in an automatic way. These automatically generated trajectories were analyzed for their higher order derivatives as well as for their frequency spectrum. These analyses suggested that continuity beyond the second or third derivatives is not always desirable.

Efforts to develop robust and efficient iterative algorithms for inverse kinematics of general robots. which were initiated under a previous USARO contract, were continued. For the position analysis of manipulators, it is common to write their governing matrix equation, say by using the 4x4 Denavit-Hartenberg matrices or the 4x4 displacement matrices, which result in an overdetermined system of nonlinear equations. An algorithm which is robust near singularities can be developed by handling this overdetermined system of equations directly, but such an algorithm is too slow. On the other hand, an efficient algorithm can be developed by selecting a particular subset of independent equations, but then the algorithm is not robust because its behavior near robot singularities is very sensitive to the choice of the particular subset. To avoid these difficulties,we have relied upon the formulations which explicitly involve the manipulator Jacobian. It is well-known that the manipulator Jacobian produces a minimal and complete set of first order relations, whether we are interested in velocities or small changes in position. Then, we have developed two types of robust and efficient algorithms. One of these uses the predictor-corrector method to solve the first order differential equations which are just the velocity Jacobian relations for the manipulator [Singh 87-*MS Thesis*][Gupta and Singh 89-*Robotica* 7:159-164] and [Cheng 89-*PhD Thesis*][Cheng and Gupta 91-*JRS* 8(2):xxx]. Another way is to formulate the Newton-Raphson type of step change by directly utilizing the manipulator Jacobian [Singh and Gupta 89-*Proc. ASME DTC/DA* 3:327-332]. Furthermore, both types of algorithms were made robust by incorporating a strict-descent feature. This feature was implemented by monitoring the error of deviation at the end-effector level and insuring that only those steps are taken which move the end-effector closer to its target position. If a step tends to increase this deviation error, it is halved successively until a decrease in the deviation error becomes possible. If even an extremely small step fails to move the end-effector any closer to its target position, then the manipulator is considered to be too close to its singularity position. The algorithm developed by [Singh 87-*MS Thesis*] paid special attention to robustness and efficiency under a serial-CPU (central processing unit of the computer) environment, while that by [Cheng 89-*PhD Thesis*] also considered these factors under a vector-CPU environment. Furthermore, Cheng demonstrated the feasibility of a completely portable, personal-computer based iterative inverse kinematics algorithm. with real-time computational capabilities.

Robot parameter estimation is an important problem for industrial robots. Due to manufacturing tolerances, or usage related degradation, the nominal values of geometry parameters may differ significantly from their actual values. The geometry parameter correction amounts were determined from numerically simulated positioning data by using a novel statistically oriented, iterative parameter identification algorithm. The formulation was based upon the development of special Jacobian matrices: $J_\theta$, $J_S$, $J_\alpha$, $J_a$ , which led to a compact and efficient scheme. An iterative compensation algorithm was developed which utilized these parameter corrections to modify the nominal parameter based closed-form solution. The influence of a fixed number of iterations upon the accuracy of compensation was also investigated [Mirman 90-*PhD Thesis*].

The effect of dynamic model errors on the performance of robot control system was considered in [Samak 89-*PhD Thesis*][Samak and Gupta 90-*Proc. ASME DTC/M* 24:73-77]. This study was conducted for some realistic types of six-axis manipulators, rather than for very simple two or three link planar manipulators. The objective was to quantitatively assess the degradation in control system performance when the geometry and mass-inertia parameters of the dynamic model were not known accurately. The conclusion was that a high degree of trajectory precision could be achieved by the controller when the geometry errors were less than 0.1% and mass-inertia errors were less than 5%. However, the trajectory precision was poor with geometry errors of 0.5-1.0% and mass-inertia errors of 25-50%. Of course, the reports of more optimistic expectations in the literature are not based upon manipulator configurations of realistic spatial complexity.

In compiling the related technical literature, we found that there were many inconsistencies of historical nature with respect to the formulas of finite rotations and their composition. This motivated us to explore this matter further in [Cheng 89-*PhD Thesis*][Cheng and Gupta 89-*ASME JAM* 56:139-145]. What we found was really surprising. The so-called Rodrigues formula for finite rotations was actually derived by Euler in one of his papers; so it should correctly be called Euler's formula for finite rotations. On the other hand, the composition formula for two successive finite rotations, which is mostly unattributed, was formally derived in an analytical way by Rodrigues in his famous paper, which was in fact a combined review/original contribution paper without a comprehensive list of earlier works. This composition formula is also identical to the multiplication rule which is later found in Hamilton's quaternion algebra. Of course, Rodrigues was specifically concerned with the practical problems of spatial rigid body rotations, while Hamilton was interested in developing a whole new system of quaternion algebra which has since been superseded by Gibbs' vectors, Cayley's matrices and Einstein' tensors. The quaternions, nevertheless, offer some practically useful advantages in applications such as spatial linkages, spacecraft dynamics, multi-body systems and molecular dynamics.

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