B. Roth, M. Raghavan, O. Khatib, and K. J. Waldron

Stanford University
Stanford, California, USA

Ohio State University
Columbus, Ohio, USA

KINEMATIC STRUCTURE FOR A FORCE CONTROLLED REDUNDANT MANIPULATOR

Abstract

We have briefly summarized the kinematic aspects of some of our work dealing with force controlled manipulators. In the first part of this paper we discuss determining a manipulator's kinematic geometry from sets of forces and moments which are required to be applied by the manipulator on the environment. In the second part we describe kinematic issues that were considered during the preliminary design phase of a new force controlled redundant manipulator. This system, named ARTISAN, has 10 degrees-of-freedom and micro-manipulation capability.

Introduction

Most mechanical manipulators are designed with position or workspace requirements as the foremost criteria in determining the kinematic parameters. Force is only considered secondarily, usually in regard to sizing actuators and transmissions. In contrast to this we have recently been involved in studies which have taken force into account in a more direct manner than has heretofore been done. This paper summarizes several of the basic ideas and results of those studies.

Designing for Specified Force and Torques

We have explored the concept of determining a manipulator's kinematic parameters from sets of forces and moments that the manipulator is required to exert on its environment. An arbitrary force and moment can always be combined into a co-axial combination called a wrench. In this paper when we use the term wrench we are referring to a force and moment. We are interested in determining the lengths and twist angles between a manipulator's joints which will allow it to apply specified wrenches or pure forces on the environment. For example, if a one link revolute manipulator is required to push with a force in a given direction then, if we neglect friction, the manipulator axis should be in a plane normal to the force. If we specify two separate positions, and a force direction is given for each position, then the revolute axis must be at the intersection of the two normal planes. This in turn means that the link length is determined and therefore also the required joint torque. So in this rather trivial example we see that for a 1R "manipulator" at most two arbitrary forces can be specified. This same idea can be extended to much more complex devices, and that has been the purpose of a portion of our recent research.

In this research we utilize the idea of free body diagrams and static equilibrium in order to determine the relationships between the design parameters, the actuator wrenches, and the wrenches applied by the manipulator to the environment. This method works very nicely for the usual types of series chains used in common manipulator designs. As an example of this consider Figure 1 which shows a simple 2R chain. If we require that this chain apply a force f and moment n to the environment along a line passing through a point **A** with a direction **U**, then the torque that needs to be applied by each actuator is given by the equilibrium equations for each link, obtained from summing the resultant torque about each joint axis. The results are that for joints 1 and 2 the actuator torque, t_1 and t_2, needs to be respectively:

$$t_1 = \mathbf{F} \cdot (n\mathbf{U} + (\mathbf{A}-\mathbf{G}) \times f\mathbf{U}) \qquad t_2 = \mathbf{M} \cdot (n\mathbf{U} + (\mathbf{A}-\mathbf{\mathcal{G}}) \times f\mathbf{U}) \tag{1}$$

Here, the first joint axis is the line with direction **F** passing through point **G**, and the second joint axis is, in the design position, the line with direction **M** through point $\mathcal{G}$.

Equations (1) are two scalar equations. If the applied wrench (n, f, **U** and **A**) is specified and the actuator torques (t_1, t_2) are specified, the set of equations contains 8 scalar unknowns (two for each of the vectors **F**, **G**, **M**, $\mathcal{G}$), and these are the parameters which define the kinematic geometry of the manipulator. Hence, if we define four different applied wrenches and four corresponding sets of joint torques, we have four sets of equations (1), and the resulting system contains 8 equations and 8 unknowns. It would be more usual to want to specify the applied wrenches at different design

Proc. International Meeting on Advances in Robot Kinematics, Ljubljana, Yugoslavia
Sept. 1988

positions. This can be easily accommodated if we introduce the rotation angle in joint 1 as a new design parameter. With this angle we can express **M**, **Q** as functions of the values they have in a reference design position. The rotation angle can be left unspecified and thus it becomes an additional design parameter every time (1) is written. If we take the first design position as the reference position, and if we specify the output wrench for 7 different design positions, and if the corresponding input actuator torques are also specified, we get from equations (1) a set of 14 scalar equations in terms of the 8 scalar linkage parameters and the 6 rotation angles for the first link (from its initial design position).

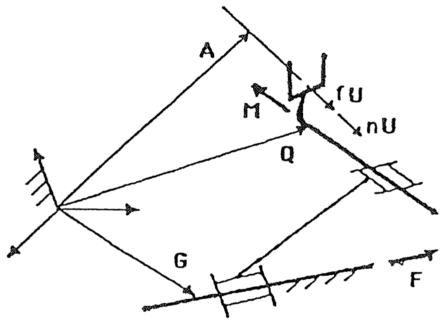

Figure 1: 2R Manipulator applying a wrench.

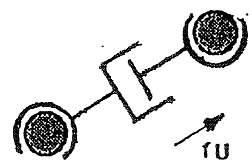

Figure 2: Force generator

For a revolute chain with j joints in series, the moment balance equation about the i^{th} joint axis yields

$$t_i = M_i \cdot (nU + (A - Q_i) \times fU) \tag{2}$$

Here, t_i is the actuator torque applied to the i^{th} joint and f, n, **U**, **A** define the output wrench which the manipulator applies to the environment in the given position. If the actuator torques and the output wrench are specified, equation (2) gives rise to j scalar equations in the 4j design parameters (2j for M_i, i=1, 2,...j and 2j for Q_i, i=1, 2,....j). If we consider a set of k design positions, and introduce the joint rotation angles in order to describe the vectors M_i, Q_i (for i=2, 3,...j) in terms of their initial design positions and their rotations from the initial design position, we have in addition to the original 4j design parameters an additional (k-1)(j-1) joint rotation parameters. Thus, equation (2) yields kj design equations in terms of 4j+(k-1)(j-1) unknown parameters. Equating the number of equations and unknowns (i.e. kj = 4j+(k-1)(j-1)) yields the maximum number of design positions: k = 3j+1. Thus, for a 5R, for example, we could specify up to 16 (i.e. 3x5+1) arbitrary wrenches and sets of input torques, and use these to determine the corresponding 20 (i.e. 4x5) linkage design parameters and the associated set of 60 (i.e. 15x4) displacement angles.

For a prismatic joint we have to replace equation (2) by

$$f_i = fU \cdot M_i \tag{3}$$

where, f_i is the actuator force applied to the i^{th} joint. The main difference here is that we now lose two design variables for each prismatic joint, since the joint's location, Q_i, does not influence the amount of force it can apply to the environment. The joint variable of course also changes. It is now a translation distance, but it is used instead of the joint rotation angle. The number of joint variables entering the design problem also changes. For any given prismatic joint, displacement at this joint does not affect the directions of the slide of the remaining prismatic joints on the outboard portion of the linkage. But, it does affect the locations of the joint axes of all revolute joints on the outboard portion of the linkage. Therefore, the joint variable associated with a particular prismatic joint enters the problem only if there is at least one revolute joint on the outboard portion of the linkage. A manipulator with p prismatic joints and r revolute joints in a series will be described by k(r+p) design equations in terms of 4r + 2p + (k-1)(r+p-1) unknown, if the last joint is revolute, 4r + 2p + (k-1)(r+p*) unknowns, if the last joint is prismatic (p* is the number of prismatic joints on the inboard side of the outermost revolute joint). Thus for a 4RP manipulator we would be able to specify at most 14 arbitrary wrenches and actuator inputs. Clearly, prismatic joints decrease the number of design positions.

The basic idea in the foregoing is to use simple equilibrium equations to derive the kinematic parameters for a manipulator. The assumptions associated with what is given and what is to be found can be modified to suit a particular situation. In our discussion we have assumed that the output wrench is fully specified in every design position. We have also assumed that the actuator torques or forces are given, and that the manipulator's structural and motion parameters are unknown. This does not have to be the case. Using the same equilibrium equations it is possible to specify some of the structural and motion parameters, and to leave the actuator or applied wrenches partially or completely unspecified. There are many possibilities even if we restrict ourselves to only revolute and prismatic joints. If we admit other types of joints we obtain a large number of other possibilities. We have analyzed many cases of 2, 3, 4 and 5 link manipulators in detail, and have provided a general framework for any number of links. Our emphasis has been on determining the theoretical limit on the maximum number of design positions for each case, and on the numerical methods which will yield all solutions to the sets of nonlinear equations which result from the static equilibrium conditions. This work is reported in detail in the Ph.D. thesis currently being completed by Madhusudan Raghavan [1].

If we attempt to apply the same design ideas to in-parallel manipulators we find that the design equations become much more complex unless we use special types of linkages. It is possible to devise groups of links which act as pure wrench generators [2]. Such assemblages have the property that certain types of wrenches inputted to the actuators are transmitted without alteration. For example, Figure 2 shows an assemblage of two links which transmits a pure force along a given line of action. By using assemblages of these pure wrench transmitting devices it is possible to devise in-parallel systems which allow for direct control of the joint forces from the driving to the driven part of the manipulator. There exist a large number of possible configurations for such in-parallel structures. Some of these structures follow directly from the usual series chains by application of the principle of duality between velocity and force [3], others can be developed in a constructive manner using the pure wrench transmitters. Their design for applied wrench generation is described in [1] and [3].

The ARTISAN structure

The foregoing ideas are useful in designing manipulators for a specific set of applications where the wrench requirements are known a priori. Our long standing interest in force application and sensor based manipulation has led us to also have a quite different set of requirements. In parallel with the above research we have been developing the design for a new force controlled manipulator which is capable of both gross and fine motion, and can operate well in situations which rely primarily on force control. In keeping with the theme of this conference, we will discuss some of the kinematic issues we have had to face during this design.

Although we have had success in adapting existing designs by adding a force sensor to a critical joint [4], and by the use of wrist and finger sensors [5], we have long felt the need for an experimental device which was specifically designed for experiments which relied primarily on force control. Several years ago, we undertook a preliminary investigation into what configuration we would want such a device to have. One of the first kinematic issues we dealt with was the question of how many degrees of freedom we wanted the device to have. We were certain that we wanted micro-manipulability, and we also wanted the ability to improve dynamic performance during large high-speed motions by altering the configuration during manipulation.

It was our goal to achieve micro-manipulation in such a way that we could have small highly precise manipulations, and yet maintain the ability to move over large ranges. These considerations led us to decide that the most practical ideas involved putting a micro-manipulation device next to the end-effector, otherwise its errors would tend to be magnified through the lever arms of the attached down-stream links. We also had the results of some studies, on impact between manipulators and their environment, which indicated strongly that the negative effects of impact can be greatly reduced if the smallest links are next to the collision [6]. So we decided to place a micro-manipulator at the free-end. Originally this implied a 12 degree-of-freedom system if we were to have full micro capability added on to full macro capability. It was decided instead to try and combine the micro and macro functions as much as possible. This lead to the idea of wrist which could provide a fairly large amount of rotation with a great degree of precision. The wrist would be the dividing point between micro and macro capability, and would be part of both portions. Much is known about wrist kinematics. Let it suffice here to say we decided upon a 3 axis wrist with intersecting axes that are arranged so that the intermediate axis is perpendicular to each of its neighbors.

From the wrist our considerations went to the macro capability. If the wrist were to be composed of three intersecting axes, the function of the macro motion portion could be reduced to simply positioning the point of intersection, i.e. the wrist's center point. Normally, this requires only 3 degrees of freedom. However, our concern to be able to change the configuration in order to improve the dynamic properties made the idea of redundancy a very appealing one. By using redundancy in the joints between the wrist and the base we could gain several important advantages: 1) We could gain some obstacle avoidance capability. 2) We could have the desired adjustability to improve inertia characteristics during the motion. 3) We could provide bracing during fine manipulations. Because of these advantages we decided to use 4 degrees of freedom between the base and the wrist point. It has been proved [7] that a spherical workspace will provide the largest work volume available to a revolute jointed manipulator. Accordingly, we chose the first two axes to be at right angles. Following the principles for maximum workspace [7], and also wishing to obtain the benefits of a locally planar structure we decided to make joints 3 and 4 parallel to each other and to joint 2. The net result is that motions in joints 2, 3, and 4 simply position the wrist center in a plane, and motion in joint 1 simply rotates this plane, see Figure 3. (In the figure, a_2, a_3 and a_4 denote non-zero link lengths.)

Thus far we have accounted for 7 degrees of freedom: 4 of which position the wrist point, and 3 are rotations about the intersecting axes in the wrist. What remains is to determine the micro-manipulator which is outboard of the wrist. Since the wrist will provide three high precision rotations, the use of a device with three prismatic axes would seem ideal. If these axes were mutually orthogonal, they could provide three decoupled high precision micro translations. However, such a device would essentially be a series chain which would tend to vibrate at frequencies that could easily be excited during manipulation. Even more importantly, by placing this device between the wrist and the working area of the gripper, the distance between the wrist concurrency point and the hand reference point is necessarily increased. The result is that the available range of rotation about axes through the reference point orthogonal to the hand axis is very small. This type of rotation is important in operations which require conforming to workpiece geometry. The best way to avoid these problems would seem to be the use of an in-parallel structure. We thus designed a 3-degree-of-freedom in-parallel micro-manipulator. With this micro-manipulator added we have 10 actuated degrees of freedom in the proposed manipulator. We have named this device ARTISAN.

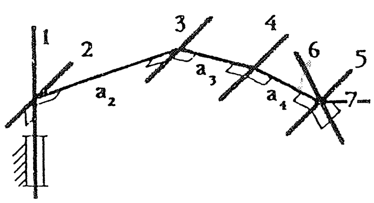

Figure 3: First 7 axes of ARTISAN

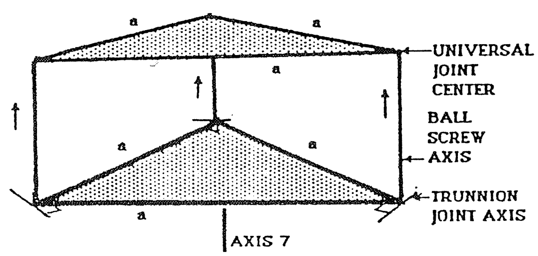

Figure 4: Micro-manipulator

The 3 actuated prismatic joints in the micro-manipulator will be implemented by the use of ball screws. Each of the three ball screws is coupled to a base plate through a passive revolute joint (called a trunnion), and to the end-effector attachment plate through a nut which is free to rotate about two transverse axes by virtue of a universal joint coupling, see Figure 4. The joint centers on the base and attachment plates are such that they form identical equilateral triangles. The entire arrangement is made as symmetric as possible to simplify the analysis and the operation.

The direct and inverse kinematics, and the velocity analysis has been worked out for this micro-manipulator [8, 9]. This in-parallel device exhibits the well known property of all in-parallel devices: the inverse kinematics is rather simple but the direct kinematics is relatively complex. In our case we can place angle measuring devices on the passive attachment joints, between the ball screws and the base plate, and by measuring rather than computing these angles we greatly simplify the direct kinematics.

The combination of series and in-parallel structure provides interesting problems in force analysis which do not seem to have been studied heretofore. Although we have derived system Jacobians, the combinations and interactions of the various substructures remains a topic of study for us. Even though we do have various analytical complexities to contend with in controlling such a system, it does seem to have many advantages from a kinematic point of view. The ARTISAN geometry allows for various modes of operation. Two of the most interesting are obtained by 1) locking the micro-manipulator so the system acts as a 7 degree-of-freedom manipulator capable of gross motion and force control, obstacle avoidance and dynamic configuration optimization. 2) Locking joints 1-4, so the system acts as a fine position-and-force controlled 6 degree-of-freedom manipulator. This design is now in the process of being finalized, we hope to soon published a detailed study describing the many aspects of this project.

Bibliography

[1] M. Raghavan, *Analytical Methods for Designing Linkages to Match Force Specifications*, Ph.D. Thesis, Department of Mechanical Engineering, Stanford University, 1988

[2] K.J. Waldron and K.H. Hunt, "Series-Parallel Dualities in Actively Coordinated Mechanisms," *Robotics Research, The Fourth International Symposium*, edited by R.C. Bolles and B. Roth, MIT Press, 1988, pp. 175-182.

[3] B. Roth, "Design and Kinematics for Force and Velocity Control of Manipulators and End-Effectors," *SDF Benchmark Symposium Volume*, MIT Press, 1988

[4] J. Farah and J. Hake, "Design of a Joint Torque Sensor for the Unimation PUMA 500 Robot Arm," *Final Report ME210, Mechanical Engineering Dept., Stanford University*, 1983.

[5] O. Khatib and J. Burdick, "Motion and Force Control of Robot Manipulators," *Proceedings of the 1986 IEEE Int'l. Conf. on Robotics and Automation*, San Francisco, CA 1986, pp. 1381-1386.

[6] C. Cai and B. Roth, "Impact Sensitivity to Mass Distribution of a Planar Manipulators," *Towards Third Generation Robotics*, edited by B. Espiau, ICAR 1987, IFS Ltd., 1987, pp. 115-124.

[7] R. Vijaykumar, K.J. Waldron and M.J. Tsai, "Geometric Optimization of Serial Chain Manipulator Structures for Working Volume and Dexterity," *The Int'l J. of Robotics Research*, Vol. 5, No. 2, pp. 91-103.

[8] K.J. Waldron, M. Raghavan, and B. Roth, "Kinematics of Hybrid Series-Parallel Manipulation System, Part I, Position Kinematics," *Modeling and Control of Robotic Manipulators and Manufacturing Processes*, edited by R. Shoureshi et al., ASME, book no. DSC-Vol. 6, 1987, pp. 127-136.

[9] K.J. Waldron, M. Raghavan, and B. Roth, "Kinematics of Hybrid Series-Parallel Manipulation System, Part II, Rate and Force Decomposition, *ibid*, pp. 137-148.