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The Mechanics of Redundantly-Driven Robotic Systems

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Progress Report

July 1992 - June 1993

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1. PROGRESS REPORT

The objectives of this research are to develop systematic methodologies for the creation of multi-DOF (Degree-of-Freedom) mechanisms and to gain better understanding of the kinematics, dynamics and control of such devices. We have continued our investigation on the following four subjects: (1) enumeration of mechanism structures, (2) gear backlash control, (3) tendon-driven manipulators, and (4) parallel mini-manipulators. In addition, we have also initiated a new project on the design of automotive transmission mechanisms. In what follows, we briefly describe the progress made and the proposed future work.

1.1 Enumeration of Mechanism Structures

In this study, we have developed an efficient algorithm for the enumeration of the topological structures of mechanisms. We use graphs to represent the topological structures of mechanisms. In the graph representation, vertices denote links, edges denote joints, and the edge labels denote the types of joint. The algorithm derives conventional graphs from contracted graphs by partitioning the binary vertices. The partition of binary vertices is then transformed into the problem of solving one linear equation in several unknown integers. Unlike Woo's method, this new algorithm requires no permutations of binary-vertex chains. This leads to the development of a highly efficient computer algorithm for the enumeration of graphs. Two tables of graphs with seven and eight vertices, and with up to five loops have been developed. Using these tables, we can now synthesize seven- and eight-link mechanisms with higher pair joints. See Hsieh and Tsai's report (1993), and Hsieh's M.S. thesis (1992) for details.

1.2 Gear Backlash Control via Redundant Drives

Chang and Tsai (1992) developed an innovative concept for the elimination of gear backlash and subsequently designed a two-DOF prototype manipulator to demonstrate the principle. Experiments conducted with the assistance of the Metrology Division at NIST indicated that the improvement in repeatability was in an order-of-magnitude.

More recently, we have designed a two-DOF wrist with three unidirectional drives to further investigate the same problem of minimizing the effect of backlash. Three different types of drivelines are considered for the design. The first assumes that all the drivelines are rigid, the second includes driveline flexibility as the primary concern, while the third replaces one of the three drivelines by a pre-stretched spring. The actuators and gears in the drivelines are carefully sized to satisfy isotropic transmission characteristics. A simulation program using computed torque control technique has been developed for the mechanism. To compare the performance and to make sure that backlash has been eliminated, reaction forces in the meshing gears have been carefully monitored. The simulation results indicate that driveline flexibility does have significant effects on

the dynamics and stability of the system. Gear rattle will occur and backlash can be completely out of control, if the controller and feedback gains are not properly designed. Details will be published in Chiang's M.S. thesis.

Backlash has a significant effect on vibration, position accuracy, and repeatability of geared servomechanisms. A simple and yet robust dynamic model is required for accurate real-time control of such mechanisms. During this reporting period, we have developed an improved model that accounts for the effect of backlash on the dynamics of spur gear systems. The complicated phenomenon of varying gear meshing stiffness as a function of contact point along the line of action has been investigated. Then, the mean-value stiffness constant is used in the proposed model. It is shown that the improved model is more realistic for real-time control to achieve high repeatability and stability of geared servomechanisms (Shing, et al, 1993).

Another major problem associated with geared servomechanism is friction. Although friction modeling has been studied extensively, most of the recent research is concerned only with friction in the journal bearings. Several researchers have investigated the phenomena of varying friction in a meshing gear pair. However, no general formula has been developed due to the complexity of coexistence of sliding and rolling friction and the effects of lubricants. Hence, it is necessary to establish a friction model that is accurate and yet not time or position dependent for the implementation of a real-time controller. Mr. Shing, a Ph.D. candidate, is currently working on this subject. Dr. Krishnaprasad of the Electrical Engineering Department serves as the co-advisor.

1.3 Tendon-Driven Manipulators

In a previous work, we investigated the force and torque transmission characteristics associated with tendon-driven manipulators. The necessary conditions for achieving isotropic transmission characteristics and for identifying a manipulator with the least maximum-tendon-force were established. It was shown that optimal tendon force distribution can be achieved for manipulators with special link proportions and tendon routings. To demonstrate the principle, an efficient algorithm for the resolution of redundancy in actuator torque was developed and a simulation study on the dynamics of a typical tendon-driven manipulator was performed (Lee and Tsai, 1992).

The above study was based on the assumptions that all pulleys mounted on the same joint axis are of the same size and the link lengths are proportioned in such a way that force transformation between the joint space and the end-effector space is isotropic at a particular manipulator posture. The flexibility in design will increase drastically if the pulleys are allowed to assume various sizes and if the link lengths can be arbitrarily proportioned. Based on this proposition, we have conducted a preliminary study. We have shown that a manipulator of general proportions can be designed to possess isotropic transmission characteristics at any

prescribed manipulator posture (Ou and Tsai, 1993). We have also shown that a manipulator designed with isotropic transmission characteristics does have better force distribution among its tendons. We now have a complete theory for the design and control of n -DOF tendon-driven manipulators with $n+1$ control tendons. We plan to extend the theory to manipulators with more than $n+1$ control tendons. This work is currently under investigation by Mr. Ou, a Ph.D. candidate.

1.4 Parallel Mini-Manipulators

Tsai and Tahmasebi (1993) conceptualized and investigated a novel class of six-DOF parallel mini-manipulators. These manipulators were configured to provide high stiffness and high resolution for fine manipulations and force control. They can be used as stand alone devices or in conjunction with a serial manipulator to form a hybrid serial-parallel manipulating system. Unlike most of the six-limbed parallel manipulators, these mini-manipulators have only three inextensible limbs to reduce the complexity and possible mechanical interference in the mechanisms.

During the previous funding period, the conceptual synthesis, the inverse kinematics, and the direct kinematics were investigated. It was shown that the inverse kinematics is a fairly straight forward problem. While the general Stewart platform manipulator has no closed-form direct kinematic solutions, the direct kinematics of these mini-manipulators can be reduced to solving an eighth-degree polynomial in the square of a single variable. Hence, given the actuator displacements, there are up to sixteen possible manipulator configurations. More recently, it was shown that the stiffness matrix of the mini-manipulator can be decoupled at the central configuration (Tahmasebi and Tsai, 1992). The singularity and workspace analysis was performed, and design guidelines were established (Tahmasebi and Tsai, 1993). See Tahmasebi's Ph.D. dissertation for more details.

1.5 Automatic Transmission Mechanisms

An automotive automatic transmission maintains a proper equilibrium between the power and torque produced by an engine and those demanded by the drive wheels. Most automatic transmissions employ some kind of epicyclic gear mechanism to achieve the above purpose. As a first step in design automation, admissible mechanism configurations that can provide the correct speed ratios, and meet other kinematic and dynamic requirements must be identified. In this work, we have introduced a canonical graph representation to uniquely identify the kinematic structures of epicyclic gear mechanisms. Structural characteristics associated functional requirements of automatic transmission mechanisms are identified. By taking some of the structural characteristics into consideration, we have developed a systematic procedure for the enumeration of epicyclic gear transmission mechanisms. The new methodology greatly increases the efficiency

of enumeration. Using this methodology, we have enumerated all the canonical graphs representing epicyclic gear transmission mechanisms with up to nine links.

The representation of mechanisms by graphs precipitates the need of a methodology for reverse transformation, that is of constructing the corresponding mechanisms from graphs. To accomplish this, we decompose a mechanism into several "fundamental gear entities." Further, we show that these fundamental gear entities are made up of five primitives, namely, sun, ring, carrier, single planet and multiple planet gears. A computer algorithm is developed to create fundamental gear entities from the graphs. These entities are then connected together to form a mechanism. The mechanism can be displayed on a computer screen by using PHIGs graphics functions. Details will be published in Chatterjee's M.S. thesis.

2. PUBLICATIONS (July 1992 - June 1993)

Chang, S.L., and Tsai, L.W., 1993, "On the Redundant Drive Backlash-Free Robotic Mechanisms," ASME Journal of Mechanical Design, Vol. 115, No. 2.

Chatterjee, G., 1993, "Enumeration and Automatic Sketching of Epicyclic-Type Automatic Transmission Gear Trains," M.S. Thesis, Mechanical Eng. Dept., University of Maryland, College Park, MD (to be published in August 1993).

Chiang, C.J., 1993, "A Comparison Study of Redundant-drive Backlash-free Robotic Wrists with Rigid and Flexible Drive Lines," M.S. Thesis, Mechanical Eng. Dept., University of Maryland, College Park, MD (to be published in August 1993).

Hsieh, H.I., 1992, "Systematic Methodologies for the Automatic Enumeration of the Topological Structures of Mechanisms," M.S. Thesis, Mechanical Eng. Dept., University of Maryland, College Park, MD.

Hsieh, H.I., and Tsai, L.W., 1993, "An Efficient Algorithm for the Automatic Enumeration of the Topological Structures of Mechanisms," ISR Technical Report, TR 93-39, also submitted for publication in the ASME Journal of Mechanical Design.

Lee, J.J., and Tsai, L.W., 1992, "Torque Resolver Design for Tendon-Driven Manipulators," ASME Mechanical Design and Synthesis, DE-Vol. 46, pp. 203-210, Scottsdale, Az., also accepted for publication in the ASME Journal of Mechanical Design.

Lin, C.C., and Tsai, L.W., 1993, "The Trajectory Analysis of Bevel Planetary Gear Trains," ASME Journal of Mechanical Design, Vol. 115, No. 1, pp. 164-170.

Ou, Y.J., and Tsai, L.W., 1993, "Kinematic Synthesis of Tendon-Driven Manipulators with Isotropic Transmission Characteristics," accepted for presentation at the 1993 ASME Design Automation Conference, also accepted for publication in the ASME Journal of Mechanical Design.

Shing, T.K., Tsai, L.W., and Krishnaprasad, P.S., 1993, "An Improved Model for the Dynamics of Spur Gear Systems with Backlash Consideration," accepted for presentation at the 1993 ASME Design Automation Conference, Albuquerque, New Mexico.

Tahmasebi, F., 1992, "Kinematic Synthesis and Analysis of a Novel Class of Six-DOF Parallel Minimanipulators," Ph.D. Dissertation, Mechanical Eng. Dept., University of Maryland, College Park, MD.

Tahmasebi, F., and Tsai, L.W., 1992, "Jacobian and Stiffness Analysis of a Novel Class of Six-DOF Parallel Minimanipulator," ASME Flexible Mechanisms, Dynamics, and Analysis, DE-Vol. 47, pp. 95-102, Scottsdale, Az.

Tahmasebi, F., and Tsai, L.W., 1993, "Workspace and Singularity Analysis of a Novel Six-DOF Parallel Minimanipulator, submitted for publication in the Journal of Applied Mechanisms and Robotics.

Tsai, L.W., and Chang, S.L., 1992, "Backlash Control via Redundant Drives: An Experimental Verification," ASME Flexible Mechanisms, Dynamics, and Analysis, DE-Vol. 47, pp. 1-10, Scottsdale, Az., also submitted for publication in the ASME Journal of Mechanical Design.

Tsai, L.W., and Tahmasebi, F., 1993, "Synthesis and Analysis of a New Class of Six-DOF Parallel Minimanipulators," Journal of Robotic Systems, Vol. 10, No. 5, pp. 561-580.

3. HONORS AND AWARDS

Visiting Professorship, University of Rome - La Sapienza, Italy, June - July, 1992

Fellow, ASME, Feb. 1992

National Science Council Lectureship Award, for world renowned scholars and scientists, Taiwan, Rep. of China, 1991-1992

NASA Certificate of Recognition, for the disclosure of an invention entitled "Six-DOF Parallel Minimanipulator with Three Inextensible Limbs"

4. PROPOSED RESEARCH

We propose to develop a computer model for the simulation of the effects of backlash and friction on the dynamics of geared servomechanisms. First, a planar one-DOF mechanism driven by a servomotor will be studied. The simulation will include the backlash and friction modeling as the fundamental concern. Advanced nonlinear control designs utilizing position, velocity, and force feedback will be developed and studied using the newly developed model. We also expect to use some of the open-loop strategies and compare our results to those available currently in the numerically controlled machine tools industry. We then plan to set up an experiment to investigate the results achieved through the simulation studies.

We propose to investigate further the two-DOF RBR wrist mechanism with flexible drive lines. Advanced nonlinear control theory using collocated and non-collocated sensors will be developed. The effects of driveline flexibility on the position accuracy, gear rattling, and stability of the system will be carefully investigated.

The kinematics, dynamics, and control of tendon-driven manipulators will continue to be of interest to us. We plan to investigate the structural and force transmission characteristics associated with n -DOF tendon-driven manipulators having more than $n+1$ control tendons. The following questions will be answered. How does tendon routing affect force transmission characteristics? What are the sufficient and necessary conditions for a manipulator with more than $n+1$ control tendons to possess isotropic transmission characteristics? How can one make better use of these extra tendons?

We also propose to develop a computer software for the design of mechanical power transmission systems. The proposed research would comprehensively integrate our recent research results, including systematic enumeration of various design alternatives, automated sketching of mechanisms, kinematic and dynamic analysis, and design optimization into an interactive computer aided engineering environment. Our goal is to greatly reduce the time it takes a current engineering team to complete the design of a high quality, easily manufactured, and energy efficient mechanical transmission system. This shall be a long term effort requiring additional support beyond the current funding period.

5. CURRENT AND PENDING SUPPORT

Project title: The Mechanics of Redundantly Driven Robotic Systems

Principal investigators: L.W. Tsai

Status: this proposal

Source of funds: Department of Energy

Amount: \$228,000

(Dr. Tsai receives 2 months of salary support each year.)

Award period: Dec. 1991 - Dec. 1994

Project title: Design and Control of a Walking Robot

(A Research and Undergraduate Education Grant)

Principal investigators: W. Dayawansa, S. Azarm, N. Farvardin, A. Tits, L.W. Tsai

Status: current

Source of funds: National Science Foundation

Amount: \$365,000

(Dr. Tsai receives 1 month of salary support each year.)

Award period: September 1992 - February 1996

6. TECHNICAL REPORTS ATTACHED

Hsieh, H.I., and Tsai, L.W., 1993, "An Efficient Algorithm for the Automatic Enumeration of the Topological Structures of Mechanisms," ISR Technical Report, TR 93-39, Also submitted for publication in the ASME Journal of Mechanical Design.

Ou, Y.J., and Tsai, L.W., 1993, "Kinematic Synthesis of Tendon-Driven Manipulators with Isotropic Transmission Characteristics," ISR Technical Report, TR 92-116, also accepted for publication in the ASME Journal of Mechanical Design.

Tahmasebi, F., and Tsai, L.W., 1993, "Workspace and Singularity Analysis of a Novel Six-DOF Parallel Minimanipulator, submitted for publication in the Journal of Applied Mechanisms and Robotics.

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