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The Mechanics of Redundantly-Driven Robotic Systems

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1 SUMMARY

The objectives of this research are to develop systematic methodologies for the creation of multi-degree-of-freedom mechanisms and to gain better understanding of the kinematics, dynamics and control of such devices. The following three inter-related subjects have been studied: (1) tendon-driven manipulators, (2) geared robotic mechanisms, and (3) automotive transmission mechanisms. The main results of this study are summarized as follows.

2 Tendon-Driven Manipulators

Tendons have been widely used to actuate compact and light-weight robot manipulators, such as dextrous mechanical hands. This is partly because it permits actuators to be installed remotely from the end-effector, and thus reducing the size and inertia of the manipulator system. Previous research on such actuation systems was accomplished primarily on the basis of specialized designs. The lack of systematic approaches has limited our ability in realizing high performance transmission systems. Therefore, the study of tendon-driven manipulators is of major importance in the field of robotics. This study is concerned with several issues of importance to enhance our understanding and design of tendon-driven manipulators.

In this study, graph is used to represent the kinematic structure of tendon-driven manipulators. It is shown that the kinematic structure of a tendon-driven manipulator is similar to that of an epicyclic gear train. Thus, the fundamental circuit equation developed for the kinematic analysis of epicyclic gear trains can be directly applied. Based on this finding, a systematic methodology for the kinematic analysis of tendon-driven manipulators is developed (Tsai and Lee, 1989).

The structural characteristics of tendon-driven manipulators and the concept of structural isomorphism are investigated from which a systematic methodology for the enumeration of tendon-driven manipulators is developed. A class of kinematic structures having pseudo-triangular structure matrices has been enumerated (Lee and Tsai, 1991a).

The transmission of forces from the actuator space to the joint space of a tendon-driven manipulator has been investigated. A criterion for differentiating force transmission characteristics and a procedure for identifying a manipulator with the least maximum-tendon-force are established. It is shown that optimal kinematic structure can be achieved for certain types of tendon routings (Lee and Tsai, 1991b).

Given a set of desired joint torques, the determination of tendon forces in an n-degree-of-freedom (DOF) tendon-driven manipulator with $n+1$ control tendons is an indeterminate problem. In this study, an efficient methodology for transforming the joint torques (n elements) to the actuator forces ($n+1$ elements) is developed (Lee and Tsai, 1993). The technique, called *torque resolver method*, utilizes two circuit-like operators to transform torques between the two different vector spaces. It can be easily programmed on a digital computer or implemented into an analog-circuit system. This technique has the potential in making a real-time computed-torque control feasible. The dynamic characteristics of a tendon-driven manipulator are also investigated. When integrating with the computed-torque control algorithm, the dynamic performance of tendon-driven manipulators is realized and identified with more fidelity (Lee and Tsai, 1995; Lee, 1991).

In the above study, it is assumed that pulleys mounted on the same joint axis are of the same size and the manipulator link lengths are proportioned in such a way that force transmission from the joint space to the end-effector space is isotropic. As an extension, the pulleys are allowed to assume various different sizes, the links are permitted take any arbitrary lengths, and the force/torque transmission characteristics from the actuator space to the end-effector space are investigated. It is shown that the actuator forces and joint torques are related by a linear transformation matrix, called the *structure matrix* while the joint torques and end-effector forces are related by a linear transformation called the *Jacobian matrix*. It is also shown that the necessary and sufficient conditions to gain a full control of an n-DOF manipulator are: (a) the minimum number of tendons required is $n+1$, (b) the rank of the structure matrix should be equal to n, and (c) there must exist at least one vector with all positive elements in the column space of the structure matrix. Using these properties, a systematic methodology for the enumeration of the kinematic structures is developed. Equations for synthesizing tendon-driven manipulators with isotropic transmission characteristics are developed. It is shown that a tendon-driven manipulator can be designed to possess isotropic transmission characteristics at any desired manipulator posture.

First, the synthesis of n-DOF manipulators with $n+1$ tendons with isotropic transmission characteristics is developed (Ou and Tsai, 1993). Then, a general theory for the synthesis of tendon-driven manipulators with more than $n+1$ tendons is explored (Ou and Tsai, 1994a). It is shown that an n-DOF manipulator can be designed to possess isotropic transmission characteristics, if its transmission system is constructed with either $n+1$ or $2n$ tendons, and if its structure matrix and Jacobian matrix are designed according to two isotropic conditions. It is also shown that manipulators designed with isotropic transmission characteristics do have more uniform force distribution among their tendons (Ou and Tsai, 1996). Finally, the properties of equal maximal tendon forces within the entire workspace were explored. It is shown that only certain tendon-driven manipulators can be designed to possess such properties (Ou and Tsai, 1994b). This investigation have answered a long standing question on the design of tendon-driven manipulators. See (Ou, 1994; Tsai, 1995) for more details.

3 Geared Robotic Mechanisms

In this study, the concept of transmission lines for the topological synthesis of articulated gear mechanisms is introduced. It is shown that the structure matrix, which relates the input displacements to the joint angles of a multi-DOF articulated gear mechanism, can be derived by using the concept of transmission lines. Using the characteristics of structure matrix, a new methodology for the topological synthesis of articulated gear mechanisms is developed. All the basic admissible structure matrices of three-DOF geared robotic mechanisms are enumerated (Chang and Tsai, 1990).

An innovative concept for the control of gear backlash in robotic mechanisms is conceived. The concept utilizes redundant unidirectional drives to assure positive coupling of gear meshes at all times. It is shown that, through a proper arrangement of gear transmission lines, backlash of an n-DOF robotic mechanism can be completely eliminated by a minimum of $(n+1)$ unidirectional drives. A methodology for the enumeration of admissible redundant-drive backlash-free robotic (RBR) mechanisms has been developed (Chang and Tsai, 1993). In order to demonstrate the concept, a two-DOF experimental RBR arm has been constructed. A computed torque PID controller is implemented in the experimental RBR robot. An experiment using a laser tracking system was conducted to verify the improvement in repeatability. In order to compare the performance difference, two control algorithms, one with redundant drives and the other without, were used in the experiment. The results indicate that use of redundant drives greatly improves the repeatability of a robot manipulator (Tsai and Chang, 1994). See Chang (1991) for more details.

The design of multi-DOF geared robotic mechanisms has also been investigated from the dynamics point of view. Firstly, a systematic methodology is developed for the dynamic analysis of geared robotic mechanisms (Chen et al., 1991). The formulation of dynamic equations is based on the concept of an *equivalent open-loop chain.* It is shown that the reaction force analysis of such mechanisms can be efficiently carried out by a forward evaluation along its transmission lines followed by a backward evaluation along the equivalent open-loop chain. Secondly, two methodologies are developed for the determination of the transmission line arrangement and the gear ratios. The first methodology considers the design from both kinematics and dynamics points of view (Chen and Tsai, 1993). It is shown that, through proper choice of gear ratios, certain gear-coupled manipulators can be designed to possess kinematic isotropy and maximum acceleration capacity at a given point. The train values of those gear-coupled manipulators can be thought of as a product of two-stage gear reductions. The second-stage gear reduction is used to define the kinematic isotropic condition while the first-stage gear reduction is used to optimize the acceleration capacity. The second methodology considers the design from just the dynamics point of view (Chen and Tsai, 1991; Chen and Tsai, 1994). It is shown that, to achieve a maximum acceleration capacity, the mass inertia matrix of the input links reflected at the joint-space should be equal to that of the major links. These methodologies provide an efficient and systematic approach for the dynamic analysis and synthesis of geared robotic mechanisms. See Chen (1991) for more details.

To further improve the accuracy and repeatability of geared servo-mechanisms, the dynamics of a geared servomechanism including backlash and frictional effects is studied and a new feedforward plus feedback control strategy is investigated. First, the dynamic model of a spur gear system with backlash and friction consideration is developed (Shing et al., 1993 and 1994). The meshing stiffness and frictional torque as functions of contact point along the line of action are studied in details. Then the mean meshing stiffness and mean frictional torque are incorporated in the model to simplify the problem. Secondly, Filippov's solution concept and his theorems are used to examine the existence and uniqueness properties of the nonsmooth dynamical system. Based on the extended stability theorems developed by Shevitz and Paden, a general methodology is developed for the analysis of stability conditions. Finally, a new open-loop optimization-based control strategy is developed. Both path generation, selection of an appropriate input function, and optimization techniques are studied in details. Finally, a methodology for finding appropriate state feedback gains to reduce possible effects of load disturbance and modeling errors is also proposed. Numerical simulation results indicate that the improvement due to this feed-forward and feedback control technique is quite satisfactory (Shing et al., 1996).

4 Automotive 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 automotive automatic transmissions employ some kind of epicyclic gear train (*EGT*) to achieve the above purpose. Typically, the central axis of an *EGT* is supported by bearings housed in a transmission case. This way, the *EGT* and the casing form a fractionated mechanism called the epicyclic gear mechanism (*EGM*). An *EGM* may possess two or more degrees of freedom depending on whether the *EGT* is a one or more-DOF gear train. In such a transmission mechanism, various speed ratios are obtained by clutching different links to the input power source and the casing of a transmission. The speed ratios selected for a transmission are tailored for fuel economy and performance, typically a first gear for starting, a second and/or third gear for passing, and a high gear for fuel economy. These speed ratios in a clutching sequence are arranged in a sequential order beginning from the first gear to the last gear followed by a reverse. A table depicting such a set of speed ratios and their clutching conditions is called a *clutching sequence.*

The first step in design automation is to enumerate admissible *EGM* configurations that can provide the desired speed ratios, and meet other kinematic and dynamic requirements. In this study, the kinematic structure characteristics associated functional requirements of an *EGM* are identified. It is shown that the kinematic structure of an *EGM* can be conveniently represented by a *canonical graph.* In a canonical graph, vertices denote links, heavy edges denote gear pairs, and thin edges denote turning pairs. The thin edges are labeled according to their axis locations in space. Furthermore, all the thin-edged paths originated form the root have distinct edge labels. By taking some of the structural characteristics into consideration, an efficient methodology for enumeration of *EGM*s is developed. All admissible canonical graphs representing *EGM*s with up to ten links have been enumerated (Chatterjee and Tsai, 1994a).

The representation of a mechanism by graph precipitates the need for a methodology for the reverse transformation, that is of constructing the corresponding mechanisms from graphs. To accomplish this goal, an *EGM* is decomposed into several fundamental geared entities (*FGE*). The *FGE*s are made up of five *primitives*: sun gear, ring gear, carrier, single planet gear, and multiple planet gears. A computer algorithm is developed to create *FGE*s from the graphs using the above five primitives. These entities are then connected together to form a mechanism which can be displayed on a computer screen by using PHIGs graphics functions (Chatterjee and Tsai, 1994b). See Chatterjee (1993) for more details.

The second step in design automation is to develop an automated computer algorithm for the speed ratio analysis of *EGM*s. The kinematic characteristics associated with various operation modes of an *FGE* are investigated. It is shown that the overall speed ratio of an *EGM* can be expressed in terms of its *FGE*s (Hsieh and Tsai, 1995).

The third step is to develop a methodology for the enumeration of various clutching sequences. The methodology we developed is based on the concept that an *EGM* can be decomposed into several *FGE*s and that the overall speed ratio of an *EGM* can be symbolically expressed in terms of its *FGE*s. First, a procedure for estimating the overall speed ratio of an *EGM*, without specifying the exact gear dimensions, is derived. Then, an algorithm for comparing various speed ratios of an *EGM* is established. Finally, a methodology for the enumeration of all possible clutching sequences associated with an epicyclic gear mechanism is developed (Hsieh and Tsai, 1996).

This development represents a giant step toward a fully automated computer-aided design of automotive transmission mechanisms.

5 Publications

1. Chang, S.L., 1991, "Redundant-drive Backlash-free Robotic Mechanisms: Creation, Analysis, and Control," Ph.D. dissertation, Mech. Eng. Dept., Univ. of Maryland, College Park, MD.

2. Chang, S.L., and Tsai, L.W., 1990, "Topological Synthesis of Articulated Gear Mechanisms," IEEE Trans. on Robotics and Automation, Vol. 6, No. 1, pp. 97-103.

3. Chang, S.L., and Tsai, L.W., 1993, "On the Redundant-Drive Backlash-Free Robotic Mechanisms," ASME Trans., Journal of Mechanical Design, Vol. 115, No. 2, pp. 247-254.

4. Chatterjee, G., 1993, Enumeration and Automatic Sketching of Epicyclic-Type Automatic Transmission Gear Trains, M.S. thesis, Mech. Eng. Dept., Univ. of Maryland, College Park, MD.

5. Chatterjee, G., and Tsai, L.W., 1994a, "Enumeration of Epicyclic-Type Automatic Transmission Gear Trains," SAE 1994 Trans., Vol. 103, Sec. 6, pp. 1415-1426, presented at the SAE 1994 Intl. Congress and Exposition, Transmission and Driveline Developments, SP-1032, Paper No. 941012.

6. Chatterjee, G., and Tsai, L.W., 1994b, "Computer Aided Sketching of Epicyclic-Type Automatic Transmission Gear Trains," accepted for publication in ASME Trans., Journal of Mechanical Design, also in ASME 1994 Design Technical Conf., Machine Elements and Machine Dynamics, DE-Vol. 71, pp. 275-282.

7. Chen, J., 1991, "Dynamic Analysis and Synthesis of Geared Robotic Mechanisms," Ph.D. dissertation, Mech. Eng. Dept., Univ. of Maryland, College Park, MD.

8. Chen, J., Chen, D.Z., and Tsai, L.W., 1990, "A Systematic Methodology for the Dynamic Analysis of Articulated Gear-Mechanisms," Japan-U.S.A. Symposium on Flexible Automation, Vol. 1, pp. 273-278, Kyoto, Japan.

9. Chen, D.Z., and Tsai, L.W., 1991, "The Generalized Principle of Inertia Match for Geared Robotic Mechanisms," IEEE Intl. Conf. on Robotics and Automation, Vol. 2, pp. 1282-1287.

10. Chen, D.Z., and Tsai, L.W., 1993, "Kinematic and Dynamic Synthesis of Geared Robotic Mechanisms," ASME Trans., Journal of Mechanical Design, Vol. 115, No. 2, pp. 241-246.

11. Chen, D.Z., and Tsai, L.W., 1994, "Synthesis of Geared Robotic Mechanisms with Maximum Acceleration Capacity," Journal of Applied Mechanisms and Robotics, Vol. 1, No. 3, pp. 17-25.

12. Hsieh, H.I., and Tsai, L.W., Dec. 1995, "Kinematic Analysis of Epicyclic-Type Transmission Mechanisms Using the Concept of Fundamental Geared Entities," accepted for publication in ASME Trans., Journal of Mechanical Design, also in ASME 1995 Design Eng. Tech. Conf., Advances in Design Automation, pp. 545-552.

13. Hsieh, H.I., and Tsai, L.W., 1996, "A Methodology for Enumeration of Clutching Sequences Associated with Epicyclic-Type Automatic Transmission Mechanisms," SAE 1996 Int'l. Congress and Exposition, Paper No. 960719, Detroit, MI.

14. Lee, J.J., 1991, "Tendon-Driven Manipulators: Analysis, Synthesis and Control," Ph.D. dissertation, Mech. Eng. Dept., Univ. of Maryland, College Park, MD.

15. Lee, J.J., and Tsai, L.W., 1991a, "On the Structural Synthesis of Tendon-Driven Manipulators Having Pseudo-Triangular Structure Matrix," Intl. Journal of Robotics Research, Vol. 10, No. 3, pp. 255-262.

16. Lee, J.J., and Tsai, L.W., 1991b, "Topological Analysis of Tendon-Driven Manipulators," 8th World Congress on the Theory of Machines and Mechanisms (IFToMM), Vol. 2, pp. 479-482, Prague, Czechoslovakia.

17. Lee, J.J., and Tsai, L.W., 1993, "Torque Resolver Design for Tendon-Driven Manipulators," ASME Trans., Journal of Mechanical Design, Vol. 115, No. 4, pp. 877-883, also in ASME 1992 Mechanisms Conf., DE-Vol. 46, pp. 203-210.

18. Lee, J.J., and Tsai, L.W., 1995, "Dynamic Simulation of Tendon-Driven Manipulators," Journal of Applied Mechanisms and Robotics, Vol. 2, No. 1, pp. 40-60, also in 1991 2nd Nat. Conf. on Applied Mechanisms and Robotics, Vol. 1, Paper No. IIB.5.

19. Ou, Y.J., 1994, "Design of Tendon Driven Manipulators with Isotropic Transmission Characteristics," Ph.D. dissertation, Mech. Eng. Dept., Univ. of Maryland, College Park, MD.

20. Ou, Y.J., and Tsai, L.W., 1993, "Kinematic Synthesis of Tendon-Driven Manipulators with Isotropic Transmission Characteristics," ASME Trans., Journal of Mechanical Design, Vol. 115, No. 4, pp. 884-891, also in ASME 1993 Design Automation Conf., DE-Vol. 65-2, pp. 467-476.

21. Ou, Y.J., and Tsai, L.W., 1994a, "Theory of Isotropic Transmission for Tendon-Driven Manipulators," ASME 1994 Design Technical Conf., Robotics: Kinematics, Dynamics and Control, DE-Vol. 72, pp. 53-61.

22. Ou, Y.J., and Tsai, L.W., 1994b, "Design of a Three-DOF Tendon-Driven Manipulator with the Characteristics of Equal Maximum Tensions," Advances in Robot Kinematics and Computational Geometry, Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 369-378.

23. Ou, Y.J., and Tsai, L.W., 1995, "Isotropic Design of Tendon-Driven Manipulators," submitted for publication, ASME Trans., Journal of Mechanical Design.

24. Shing, T.K., Tsai, L.W., and Krishnaprasad, P.S., 1993, "An Improved Model for the Dynamics of Spur Gear Systems with Backlash Consideration," Proc. of the ASME Design Automation Conf., DE-Vol. 65-1, pp. 235-244.

25. Shing, T.K., Tsai, L.W., and Krishnaprasad, P.S., 1994, "Dynamic Model of a Spur Gear System with Backlash and Friction Consideration," Proc. of the ASME Design Technical Conf., DE-Vol. 71, Machine Elements and Machine Dynamics, pp. 155-163.

26. Shing, T.K., Tsai, L.W., and Krishnaprasad, P.S., 1996, "A Feedforward and Feedback Control Strategy for Geared Servomechanisms," submitted for presentation at the American Control Conference, Japan.

27. Tsai, L.W., 1995, "Design of Tendon-Driven Manipulators," ASME Trans., A Special Combined Issue of the Journal of Mechanical Design and Journal of Vibration and Acoustics, Vol. 117(B), pp. 80-86.

28. Tsai, L.W., and Chang, S.L., 1994, "Backlash Control via Redundant Drives: An Experimental Verification," ASME Trans., Journal of Mechanical Design, Vol. 116, No. 3, pp. 963-967.

29. Tsai, L.W., and Lee, J.J., 1989, "Kinematic Analysis of Tendon-Driven Robotic Mechanisms using Graph Theory," ASME Trans., Journal of Mechanisms, Transmissions, and Automation in Design, Vol. 111, No. 1, pp. 59-65.

6 Patent Issued

Anti-Backlash Drive Systems for Multi-Degree Freedom Devices, U.S. Patent No. 5,245,263, with S.L. Chang, September 1993.

7 Development of Human Resources

The following students have been supported either in whole or in part by this research grant: Y.J. Ou (Ph.D., Spring 1994), D.Z. Chen (Ph.D., Fall 1991), J.J. Lee (Ph.D., Spring 1991), S.L. Chang (Ph.D., Fall 1990), G. Chatterjee (M.S., Summer 1993), and H.I. Hsieh (M.S., Fall 1992, Ph.D. in progress). In addition, some of the results of this research have been incorporated in two graduate courses, ENME603 – Advanced Mechanisms and Robot Manipulators, and ENME604 – Systematic Design of Mechanisms.

8 Technical Reports Attached

Reprints removed for separate processing

1. Chang, S.L., and Tsai, L.W., 1990, "Topological Synthesis of Articulated Gear Mechanisms," IEEE Trans. on Robotics and Automation, Vol. 6, No. 1, pp. 97-103.

2. Chang, S.L., and Tsai, L.W., 1993, "On the Redundant-Drive Backlash-Free Robotic Mechanisms," ASME Trans., Journal of Mechanical Design, Vol. 115, No. 2, pp. 247-254.

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7. Hsieh, H.I., and Tsai, L.W., Dec. 1995, "Kinematic Analysis of Epicyclic-Type Transmission Mechanisms Using the Concept of Fundamental Geared Entities," accepted for publication in ASME Trans., Journal of Mechanical Design, also in ASME 1995 Design Eng. Tech. Conf., Advances in Design Automation, pp. 545-552.

8. Hsieh, H.I., and Tsai, L.W., 1996, "A Methodology for Enumeration of Clutching Sequences Associated with Epicyclic-Type Automatic Transmission Mechanisms," SAE 1996 Int'l. Congress and Exposition, Paper No. 960719, Detroit, MI.

9. Lee, J.J., and Tsai, L.W., 1991, "Topological Analysis of Tendon-Driven Manipulators," 8th World Congress on the Theory of Machines and Mechanisms (IFToMM), Vol. 2, pp. 479-482, Prague, Czechoslovakia.

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11. Ou, Y.J., and Tsai, L.W., 1993, "Kinematic Synthesis of Tendon-Driven Manipulators with Isotropic Transmission Characteristics," ASME Trans., Journal of Mechanical Design, Vol. 115, No. 4, pp. 884-891, also in ASME 1993 Design Automation Conf., DE-Vol. 65-2, pp. 467-476.

12. Ou, Y.J., and Tsai, L.W., 1995, "Isotropic Design of Tendon-Driven Manipulators," submitted for publication, ASME Trans., Journal of Mechanical Design.

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14. Tsai, L.W., 1995, "Design of Tendon-Driven Manipulators," ASME Trans., A Special Combined Issue of the Journal of Mechanical Design and Journal of Vibration and Acoustics, Vol. 117(B), pp. 80-86.