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THE DESIGN OF A HIGH-PERFORMANCE FORCE-CONTROLLED MANIPULATOR

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Abstract: The paper describes the basic concepts behind the design of a ten-degree-of-freedom robot manipulator, named ARTISAN, currently being constructed a Stanford University. The major goal of the design of ARTISAN has been to develop the technology for a new generation of force-controlled robot systems to overcome the deficiencies inherent in conventional robot mechanisms and to provide the advanced capabilities needed for carrying out dextrous manipulation tasks. High performance joint torque control, optimal dynamic properties at the end-effector, motion redundancy, fine manipulation ability, and integrated sensing have been the basic characteristics we have addressed in the design of ARTISAN. In addition to outlining the reasons for our specific design choices, the paper discusses the several analytical results that led to these choices in the design of ARTISAN.

Keywords: Manipulator design, torque sensing, force control, optimal dynamic characteristics, mini-manipulator, motion redundancy.

INTRODUCTION

Current manipulator technology relies almost exclusively on the concept of joint position control. This type of control has proven to be adequate for some industrial tasks, such as material handling, spray painting, and welding. However, these robots have made few inroads into applications that required higher skills and dexterity. For example, compliant parts assembly, surface finishing, and composite material lay up require capabilities which cannot be found in today's industrial robots.

At Stanford University, we have long felt the need for a new generation robot designed especially to facilitate experiments in force control. Four years ago we launched a major effort to design and construct a high-performance force-controlled macro-/mini-manipulator system. The major goal of this project has been to develop the technology for a new generation of force-controlled robot systems to overcome the deficiencies inherent in conventional robot mechanisms and to provide the advanced capabilities needed for carrying out dextrous manipulation tasks.

This paper discusses the basic concepts behind the ARTISAN project and describes the mechanical design of this macro-/mini-manipulator system.

ARTISAN

The ARTISAN design addresses a number of basic capabilities by incorporating several novel features. These capabilities are:

High-performance joint-torque control:

Typical manipulators transmit actuator torque to the joints through gear systems with high gear ratios. Gears are prone to cogging, backlash, and various types of friction which considerably restrict the ability to control joint torques. In recent years, there have been several efforts to obtain good joint torque control. Direct-drive arms have been developed at MIT, CMU, Adept, and elsewhere. However, direct-drive arms require relatively massive actuators and are more sensitive to dynamic perturbations. The solution we have adopted in our design has been to combine a low gear reduction with joint torque feedback.

Fine-manipulation ability: The ability of a manipulator to perform *fine motions* can be greatly enhanced by incorporating a set of small lightweight links – a mini-manipulator – into the manipulator mechanism. Also, the light weight links of a mini-manipulator allow a great reduction of the negative effect of an impact between the manipulator and its environment (Cai and Roth 1987). The effective inertia of a macro-/-mini-manipulator system is upper bounded (Khatib 1988) by the inertial properties of the lightweight mini-manipulator. It is essential that the range of motion of the joints associated with the mini-structure allows accommodation for the relatively slower dynamic response of the arm. This has been one of the basic considerations in the design of the mini-manipulator portion of ARTISAN.

Gross-motion redundancy: In addition to the extra degrees of freedom, or redundancy, which result from incorporating a mini-manipulator structure, gross motion redundancy is also desirable. Redundancy is important for extending the capability of robots in applications requiring complex tasks and workplaces. By appropriate additions of motion redundancy, a system's utility can be markedly improved. For these reasons we have provided for a seven-degree-of-freedom gross motion, kinematically optimized structure.

Dynamic performance: The dynamic performance of a manipulator is strongly dependent on its inertial and acceleration characteristics as perceived at the end-effector. Optimization of a manipulator's parameters during the design process can significantly improve its dynamic performance. If a design can provide small, isotropic, and uniform end-effector inertial prop-

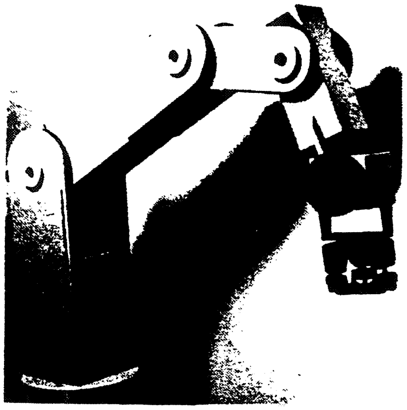

Figure 1. A Model of ARTISAN

erties the manipulator will be capable of fast, isotropic, and uniform dynamic response and will be capable of achieving large, isotropic, and uniform bounds on the magnitude of end-effector acceleration.

A photograph of a full scale model of this redundant ten degree-of-freedom robot is shown in Figure 1.

KINEMATIC STRUCTURE

One of the first kinematic issues we dealt with was the question of how many degrees of freedom we wanted the device to have. It was our goal to achieve small highly precise manipulations, and yet maintain the ability to move over large ranges. Placing a mini-manipulation device next to the end-effector would result into a 12-degree-of-freedom system if we were to provide for full mini-manipulation capability to be added on to the full macro-manipulation capability. It was decided instead to try and combine the macro- and mini- 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 the macro- and mini-manipulation ability, 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, joint motion limits imposed by mechanical interference can severely restrict kinematic performance. In fact, six-degree-of-freedom industrial robots perform effectively as five-degree-of-freedom devices. These considerations, in addition to our desire of providing the ability to modify the manipulator configuration in order to improve its dynamic properties made the idea of redundancy a very appealing one.

Gross Motion Redundancy

It has been proved (Vijakumar, Waldron, and Tsai 1986) 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, and also wishing to obtain the benefits of a locally planar structure we decided to make joints 3 parallel to joint 2. The net result is that motions in joints 2, and 3 simply position the wrist center in a plane, and motion in joint 1 simply rotates this plane.

We have decided to add a joint (joint 4) to the arm/wrist structure creating a kinematically redundant system. The addition of this joint provides some obstacle avoidance capability for the positioning of the wrist and relaxes the kinematic optimality constraints on the distances between axes allowing additional freedom for dynamic optimization.

In order to compensate for the limited motion range of the first wrist axis, the additional joint must be parallel to and reasonably close to that joint. Axis 4 is therefore selected parallel to axis 3. This selection also allows the avoidance of the singularity of the second wrist axis (joint 6).

Mini-Manipulator Structure

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 mini-manipulator which is outboard of the wrist.

The mini-manipulator geometry was to be optimized in order to provide high resolution and high bandwidth of both forces and positions on the mini-manipulator axes. However, it was desired that the ranges of motion be sufficient to provide adequate performance as a fine manipulation system when used in combination with 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 mini 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. The best way to avoid this appeared to be the use of an in-parallel structure.

Parallel chain structures are inherently stiffer than serial chain mechanisms. The cost is relatively limited motion ranges. Obviously, this is not constraining in a mini-manipulator intended to have restricted motion ranges. Early in the project, use of a Stewart platform geometry for the mini-manipulator was considered. This is a full six degree of freedom parallel mechanism. However, because of its restricted rotation capability it could not perform the functions of both wrist and mini-manipulator.

We thus designed a three-degree-of-freedom in-parallel structure. The 3 actuated prismatic joints are implemented by the use of ball screws. Each of the three ball screws is coupled to a base plate through a passive revolute joint, 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, as shown in Figure 2. 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 lowest natural frequency of this system with maximum load is estimated to be above 150Hz.

The direct and inverse kinematics, and the velocity analysis has been worked out for this structure (Waldron, Raghavan, and Roth 1987). 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. We have

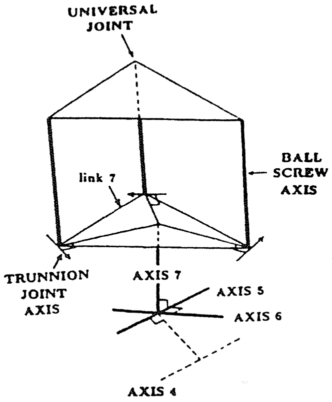

Figure 2. In-Parallel Structure

placed 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.

Joint Torque Capability

The list of desirable properties for high performance joint torque control includes: high backdriveability, low friction, minimal effects of ripple torques, and little backlash. These properties clearly point toward transmission systems with low gear ratios. The design we have adopted for the actuation of ARTISAN has been to use a single stage low gear reduction, which minimizes transmission nonlinearities, and to actively compensate for these nonlinearities through joint torque servoing using torque sensing.

Motor and Transmission Selection

The actuation of ARTISAN uses brushless (permanent magnet) motors and a single stage, low gear reduction (evoloid) system with torque sensing. Joint torque feedback is aimed at reducing friction and transmission effects, thus providing high performance joint torque control. The goal is to provide, for each joint, an independent, high-bandwidth, robust torque servo controller. The gear ratios for the arm and wrist axes are in the range of 20:1 to 30:1. Since peak torque varies approximately linearly with motor weight, a 20:1 reduction provides a 20 fold increase in available joint torque at a weight of no more than 2 times that of the motor alone, rather than a 20 fold increase in the weight as would be required for a direct drive motor.

Each motor is mounted at the base of its link in order to counterbalance the link's mass. The motor torque is transmitted through double-ended shaft in parallel to two single-stage low gear-reduction transmissions, allowing lower load at each gear. A shaft encoder is located on the motor axis to measure the relative position between the link and the motor. A prototype link for ARTISAN is shown in Figure 3.

The requirements of compactness and light weight for the three-degree-of-freedom in-parallel device has dictated the use of small motors with relatively high reduction ratios. Ball screw drives were used for the mini-manipulator with a reduction ratio of 305:1.

Joint Torque Sensor Design

Breakaway friction for high geared manipulators with brush type servo-motors such as the PUMA is much higher (more then an order of magnitude) than the friction resulting from the brushless dc motors of the low geared prototype of ARTISAN. To bring about a reduction of the already low friction, high torque accuracy is needed for the sensor. The required resolution (torque accuracy to maximum torque) for the sensor has been estimated as 0.03%.

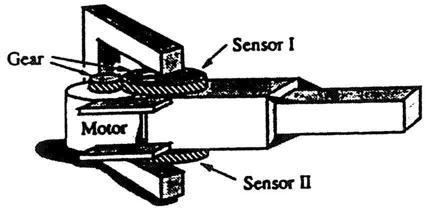

Figure 3. Prototype Link

We at first attempted to use a strain gauge torque sensor. We used the four beam design shown in Figure 4. Beam deflection was measured by semiconductor strain gauges. Eight strain gauges arranged in Wheatstone bridges were used for each of the two sensors integrated in the two gears attached to each motor.

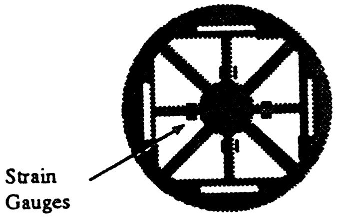

Figure 4. Strain Gauge Sensor

With this type of sensors, gear eccentricities resulted in a position-dependent torque offset, which was 5 to 10 times higher than the required accuracy. The use of lookup tables to compensate for this dependency resulted in significant improvements but did not allow us to obtain the required resolution of 0.03%.

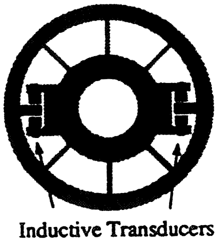

Figure 5. Contact-less Inductive Torque Sensor

Our investigation of alternative devices for torque sensing has resulted in a conceptually new torque sensor (Vischer and Khatib 1989). With this new sensor, torques are obtained from measurements of beam deflections using contact-free distance sensors. The layout of the new sensor is shown in Figure 5. The sensor uses a six beam structure. Four inductive transducers are arranged in a Wheatstone bridge configuration. The signal-to-noise ratio of the new sensor is 24 times higher than the value obtained with the initial sensor.

This contact-less sensor is mechanically more robust than strain gauge sensors. Inductive sensors are housed in steel cases and can withstand torques that are at least one order of magnitude higher than the maximum measurable torque, whereas strain gauges are

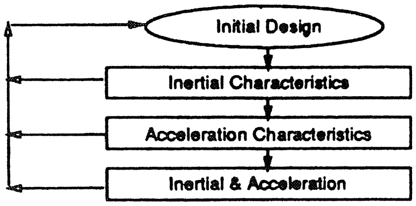

Figure 6. Dynamic Optimization Procedure

quite fragile and tend to break easily. Their maximum allowable strain is also fairly close to the strain at which they break, making failure prevention difficult. Another shortcoming of strain gauges is their sensitivity to electrical noise. With the new sensor, the inductive bridge is modulated with a carrier frequency of 5 kHz, which significantly reduces the sensitivity to electrical noise.

DYNAMIC OPTIMIZATION

The dynamic performance of a manipulator with respect to its end-effector is described by the inertial and acceleration characteristics as perceived at the end-effector operational point. The inertial characteristics at this point are given by the operational space kinetic energy matrix which is dependent on the manipulator kinematic and inertial parameters and varies with its configuration. The acceleration characteristics of the end-effector are described by a joint torque/acceleration transmission matrix. Like the kinetic energy matrix, this joint torque/acceleration matrix is dependent on the manipulator kinematic and inertial parameters and varies with its configuration. In addition, this matrix is dependent on the actuator torque bounds.

The dynamic optimization is aimed at obtaining the most isotropic and most uniform end-effector inertial properties while providing the largest, most isotropic, and most uniform bounds on the magnitude of end-effector acceleration. In our search of optimal design parameters, workspace and kinematic considerations were used first to determine the set of possible kinematic configurations of the mechanism. The parameters associated with each of these kinematic configurations were specified within some design boundaries. These kinematic specifications, in addition to dynamic and structure requirements, established various constraints on the manipulator design. The dynamic optimization was then formulated (Khatib and Agrawal 1988) in terms of finding, under these constraints, the design parameters that provide the smallest, most isotropic, and most uniform inertial characteristics at the end-effector; and the largest, most isotropic, and most uniform bounds on the magnitude of end-effector acceleration, at both low and high velocities.

The design optimization problem was expressed as a minimization throughout the workspace of a cost function with respect to the kinematic, dynamic, and actuator design parameters and their constraints. This cost function was made up of three costs, one comes from the inertial characteristics, while the other two come from the costs associated with the end-effector acceleration at zero and maximum velocity.

The optimization was conducted in three main steps, as illustrated in Figure 6. Based on the preliminary design, the inertial characteristics were first optimized. This resulted in a initial selection of link dimensions and its mass distribution. The second step of optimization involved the selection of motor torques to achieve optimal acceleration characteristics. In the final step, the design obtained from the two above steps was used as the initial guess for the overall optimization. This three step optimization led to a reduction of the search space in the first two steps and provided a good initial guess for the final step of the optimization.

This dynamic optimization has resulted in a set of optimized link lengths, masses and inertias, which were used for the ARTISAN structure. The optimized dynamic of ARTISAN were compared to those of a PUMA 560 arm. The average effective mass of ARTISAN carrying an 8kg of load is 53kg, much lower than that of the PUMA evaluated without a load (66kg). For ARTISAN, the average value of the condition numbers, which characterize the inertial isotropicity, is 4. This number is three times higher for the PUMA. The average value of the minimum available accelerations of ARTISAN carrying an 8kg of load (4g) is four times that of the PUMA (without a load).

CONCLUSION

In this paper, we have described the design concepts of ARTISAN, a redundant ten-degree-of-freedom manipulator and mini-manipulator system. The basic capabilities we have addressed in the design of ARTISAN are: high-performance joint-torque control ability, optimal dynamic characteristics, motion redundancy, and fine manipulation ability. ARTISAN is expected to constitute a unique test-bed for conducting the experimental work connected to many aspects of force-based control methodologies.

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