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New Robot Mechanisms for New Robot Capabilities

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Abstract

Recent trends and developments in robotics clearly suggest the need for a new generation of robot systems to overcome the deficiencies inherent in conventional manipulator mechanisms. Joint torque control ability, optimal dynamic characteristics, motion redundancy, and fine manipulation ability are among the basic characteristics that would be desirable attributes of a new generation of advanced robot systems. The paper discusses the limitations of current robot technology and describes the ongoing effort at Stanford University for the development of high-performance force-controlled robot systems to provide the advanced capabilities needed for carrying out dextrous manipulation tasks.

Introduction

Reliable and accurate robots are today commercially available and are successfully used in a broad range of industrial tasks. Robot applications include material handling, inspection, spray painting, tool loading, and welding. However, robots have made few inroads into applications that require 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.

These missing capabilities are the result of a combination of difficulties in several component areas of robotics. Among the key problems, for which solutions will have far-reaching consequences in many application areas, are the problems inherent in the current technology which prevent robot manipulators from achieving high-bandwidth control of forces and compliant motions. The limitations associated with using current state-of-the-art technology have considerably restricted the transfer to industry of many advanced control techniques and have also affected the research in many laboratories. Presently, most laboratories are handicapped by the need to use devices that were essentially designed for position control.

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 provide the advanced capabilities needed for carrying out dextrous manipulation tasks.

The paper discusses the limitations of conventional robot mechanisms, describes the desirable attributes of a new generation of advanced robot systems, and presents the design effort at Stanford University for the development of high-performance force-controlled robot systems.

Missing Capabilities

Force control has emerged as one of the basic means to extend robot capabilities in performing advanced manipulation tasks. To date, virtually all commercial robots are restricted to simple position controlled operations. To be cost-effective, a robot system must be fast. While high speed can be achieved with a conventional PID controller in point-to-point tasks, a much different control technique and a much different robot technology are needed for advanced robot applications.

There have been many advances in the approximately 30 years that robot mechanisms and control systems have been studied. The efforts in mechanical design have produced significant improvements in the kinematic characteristics of the basic manipulator geometries. In addition, a number of new robotic devices have been developed: such as multi-fingered hands (JPL/Stanford hand, Utah/MIT hand), mini-manipulators, and a variety of end-effectors equipped with force, tactile, and range sensors.

In regard to robot dynamics and control, significant research advances have taken place: efficient algorithms to obtain the dynamic equations of motion have been developed; grasping and contact forces have been analyzed; new techniques for force control, adaptive control, and cooperative control of multiple manipulators and dextrous hands have been proposed.

On the factory floor, however, despite these advances, PID controllers dominate. With PID controllers, the dynamic interactions between joint motions are ignored and each joint is independently controlled. The implementation of PID control is quite simple, and the performance of PID controllers has been sufficient for many industrial tasks. However, the performance of PID controllers decreases when dynamic effects become significant. The undesirable effects increase with the range of motion, speed, and acceleration at which the robot is operating and become a major factor in high-speed assembly-type operations.

The barriers to implementing advanced control techniques on robots on the factory floor go beyond the comparative advantages of simplicity and modest computing requirements of PID controllers. The difficulty is inherent in the mechanical technology of today's robots, with its reliance on a position control modality. A prerequisite to dynamic control implementation is the ability to achieve precise control of joint torques. The ability to control joint torque is, however, considerably restricted by the nonlinearities and friction inherent in the actuator-transmission systems used in most industrial robots.

Robot joint torque control is essential not only for achieving higher dynamic performance through the implementation of dynamic control techniques, but also for the implementation of force-based assembly and surface finishing operations. In assembly tasks, the robot is required to control contact forces while compensating for the dynamic forces induced by the robot's physical interaction with the mating parts. For surface finishing tasks which involve large motions while maintaining effective control of forces, dynamic compensations for the additional inertial forces become critical for achieving accuracy at high speeds.

Even in tasks such as circuit board assembly, where conventional robots are widely used, their inherent limitations lead to expensive solutions. For example, the use of position controlled robots for assembly tasks results in tight constraints on manipulator accuracy in order to achieve precise part placement. These constraints lead, in turn, to massive, rigid, slow manipulators, and to costly and complex part feeding and fixturing devices.

The inability of position-controlled robots to provide explicit control of forces has lead to partial solutions, which are based on the use of passive compliance devices (RCC) or controllers which attempt to regulate the position/velocity control to produce effective stiffness/damping in order to implement compliant motion and force control. However, the success of these schemes has been limited to quasi-static operations, and their dynamic performance has been very limited.

Higher velocities result in higher dynamic interaction forces between the moving links; active compensation for the effects of these forces is then required for achieving dynamic accuracy. Techniques for dynamic decoupling and motion control are well developed. However, their implementations require a basic capability for joint torque control, which cannot be found in conventional manipulators.

Dealing with the robot's dynamics and achieving high-performance force control require joint torque control capabilities to compensate for the dynamic effects and to explicitly control the active forces. In addition, high-performance control of forces and motions requires the robot structure to have a high mechanical bandwidth. Incorporating lightweight links, e.g. micro- or mini-manipulators, at the end-of-arm can greatly contribute to bandwidth improvement.

There has, indeed, been a gap between the technology in robot mechanical design and the techniques developed in robot control. In a sense, the effort in robot modeling and control went beyond the capabilities offered by today's robot mechanisms. The developments in regard to robot mechanisms have led to important progress in enhancing workspaces and improving kinematic characteristics. However, these developments have failed to address the basic requirements for advanced control of these mechanisms, i.e. the need for joint torque control.

Toward a New Generation

Manipulator technology has been driven by position control considerations. These systems are not capable of dealing with dextrous tasks requiring high performance force control capability. The basic capabilities needed in robot manipulator systems 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. The ability to control joint torque is considerably restricted by the nonlinearities and friction in these transmission systems. In the last ten years, there have been several efforts to improve joint torque control with joint torque sensing. Based on experiments with a single joint (Wu and Paul, 1980), the first two joints of a Stanford Arm were redesigned (Luh, Fisher, and Paul, 1983) to accommodate torque sensors. Joint torque sensory feedback has also been implemented (Asada, Youcef-Toumi, and Lim, 1984) in a direct-drive manipulator and in a PUMA manipulator (Pfeffer, Khatib, and Hake, 1986).

These experiments have shown that, although joint friction effects can be substantially reduced by torque servoing, a wide joint actuation bandwidth is difficult to achieve without actually reducing the friction and non-linearities in the actuator-transmission system. Another line of research has been directed at the development of direct-drive arms. Since the first development of a direct-drive arm at CMU in 1981 (Asada and Kanade 1983), several other designs were proposed and direct-drive manipulators became commercially available. However, direct-drive arms require relatively massive actuators. Additionally, direct-drive manipulators are more sensitive to dynamic coupling, and thus will be more susceptible to dynamic modeling errors and dynamic perturbations.

An interesting solution can be found in combining low gear reductions with joint torque feedback compensations. This approach is being used in the actuation of the new manipulator system under development at Stanford.

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 (Tilley, Cannon, and Kraft 1986; Sharon, Hogan, and Hardt, 1988). Clearly, the higher accuracy and greater speed of a mini-manipulator are useful for small motion operations (during which the rest of the manipulator can be held motionless). Also, the lightweight 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). During force control operations, a mini-manipulator can be used to overcome manipulator errors in the directions of active force control by using end-effector force sensing to perform small and fast adjustments. However, improvement in the dynamic performance due to lightweight links is not limited to small motion tasks or to constrained motion operations.

Investigating the inertial characteristics of manipulator structures, we have shown (Khatib 1988) that the effective inertia of a macro/mini-manipulator system is upper bounded by the inertial properties of the lightweight mini-manipulator structure. Mechanical limits on the range of joint motions of the mini-manipulator can cause difficulty since these desirable characteristics are only useful within the available range of the mini-manipulator motions.

A dextrous dynamic coordination strategy was developed to extend the high-bandwidth properties to operations involving large ranges of motion. This strategy is based on the minimization of the deviation from the neutral (mid-range) joint positions of the mini-manipulator. This minimization is achieved by controlling the manipulator's internal motions, while the end-effector is performing its task. Eliminating the dynamic interaction between these two tasks is a primary concern. This is realized by controlling the internal motions with joint forces selected from what we call the dynamically consistent null space.

With this approach, the response time of the manipulator system can be reduced and made comparable to the response time of the high-bandwidth mini-manipulator over large areas of the workspace. This result has important implications on the dynamic performance of many large, massive, and extended manipulators. However, 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. A sufficient motion margin is required for achieving dextrous dynamic coordination. This has been one of the basic considerations in the design of the mini-manipulator portion of the robot manipulator under development at Stanford.

Gross-Motion Redundancy: In addition to the 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. Manipulators with six degrees of freedom can generally realize an arbitrary position and orientation of the end-effector. However, this becomes impossible if certain joint movements are precluded by obstacles. The workspace of a six-degree-of-freedom arm has to be carefully structured, and motions have to be carefully planned to satisfy obstacle constraints. By appropriate additions of motion redundancy, a system's utility can be markedly improved.

Dynamic Performance: A manipulator's dynamics are highly nonlinear, and its dynamic parameters vary with position. In addition manipulators are coupled systems since motions of the links influence each other. The dynamic characteristics are, therefore, essential considerations in the analysis, design, and control of these mechanisms. Asada proposed the generalized inertia ellipsoid (Asada 1983) as a tool for the characterization of manipulator dynamics and Yoshikawa has extended the *measure of manipulability* (Yoshikawa 1983) to a *measure of dynamic manipulability* (Yoshikawa 1985).

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 properties 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.

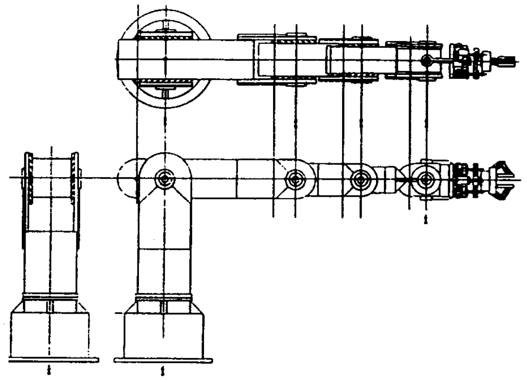

Figure 1: Kinematic Structure of ARTISAN

ARTISAN

The capabilities discussed above are directly affected by the design of a robot's mechanical structure and actuation system. The development of a system that can provide these capabilities has been the goal of the ARTISAN design project (Khatib, Roth, and Waldron 1991). Our study has lead to a new kinematic structure consisting of a redundant ten degree-of-freedom mechanism which incorporates mini-manipulation ability designed to operate effectively under force control. The kinematic structure of this redundant ten-degree-of-freedom robot is shown in Figure 1.

This device is a hybrid in-parallel/series structure. The first seven degrees of freedom are in the form of a series chain with revolute joints. The last three of these seven joints form a three-degree-of-freedom wrist. ARTISAN's last three active degrees of freedom are incorporated in the form of an in-parallel structure; driven by ball-screws which effectively act as prismatic joints. This in-parallel structure (Waldron, Raghavan, and Roth 1989) is mounted to the end of the wrist in such a way that the last six degrees of freedom of ARTISAN can act as a six degree-of-freedom mini-manipulator.

Joint Torque Control 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.

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.

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 of ARTISAN wrist structure is shown in Figure 2.

Our investigation of torque sensing devices 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. 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 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, which significantly reduces the sensitivity to electrical noise.

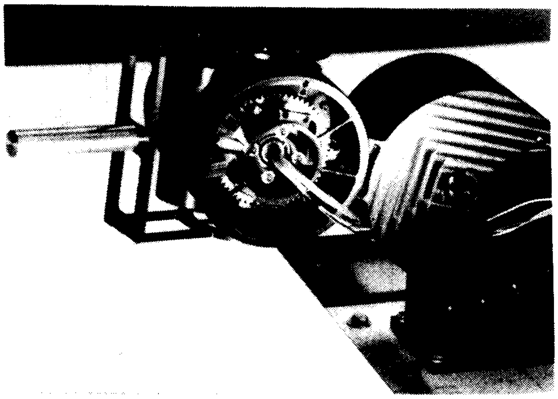

Figure 2: Wrist Structure Prototype

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. This dynamic optimization has resulted in a set of optimized link lengths, masses and inertias, which were used for the ARTISAN structure.

Conclusion

Force control has emerged as one of the basic means to extend robot capabilities in performing advanced manipulation tasks. In this paper, we have discussed the limitations of current manipulator technology for achieving responsive force control and described the basic characteristics that should be addressed in the design of a new generation of advanced robot systems. The paper also 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. The major goal of the design of ARTISAN has been to develop the technology of force-controlled robot systems with advanced capabilities needed for carrying out dextrous manipulation tasks.

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