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A Macro-Micro Robot for Precise Force Applications

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Abstract

This paper describes an 8 degree-of-freedom macro-micro robot capable of performing tasks which require accurate force control. Applications such as polishing, finishing, grinding, deburring, and cleaning are a few examples of tasks which need this capability. Currently these tasks are either performed manually or with dedicated machinery because of the lack of a flexible and cost effective tool, such as a programmable force-controlled robot.

The basic design and control of the macro-micro robot is described in this paper. A modular high-performance multiprocessor control system was designed to provide sufficient compute power for executing advanced control methods. An 8 degree of freedom macro-micro mechanism was constructed to enable accurate tip forces. Control algorithms based on the impedance control method were derived, coded, and load balanced for maximum execution speed on the multiprocessor system.

Introduction

There are two main difficulties have made impeded the development of a high-precision force controlled robot. The execution of control strategies which enable precise force manipulations are difficult to implement in real time because these algorithms have been too computationally complex for available controllers. Also, a robot mechanism which can quickly and precisely execute a force command is difficult to design. Actuation joints must be sufficiently stiff, frictionless, and lightweight so that desired torques can be accurately applied.

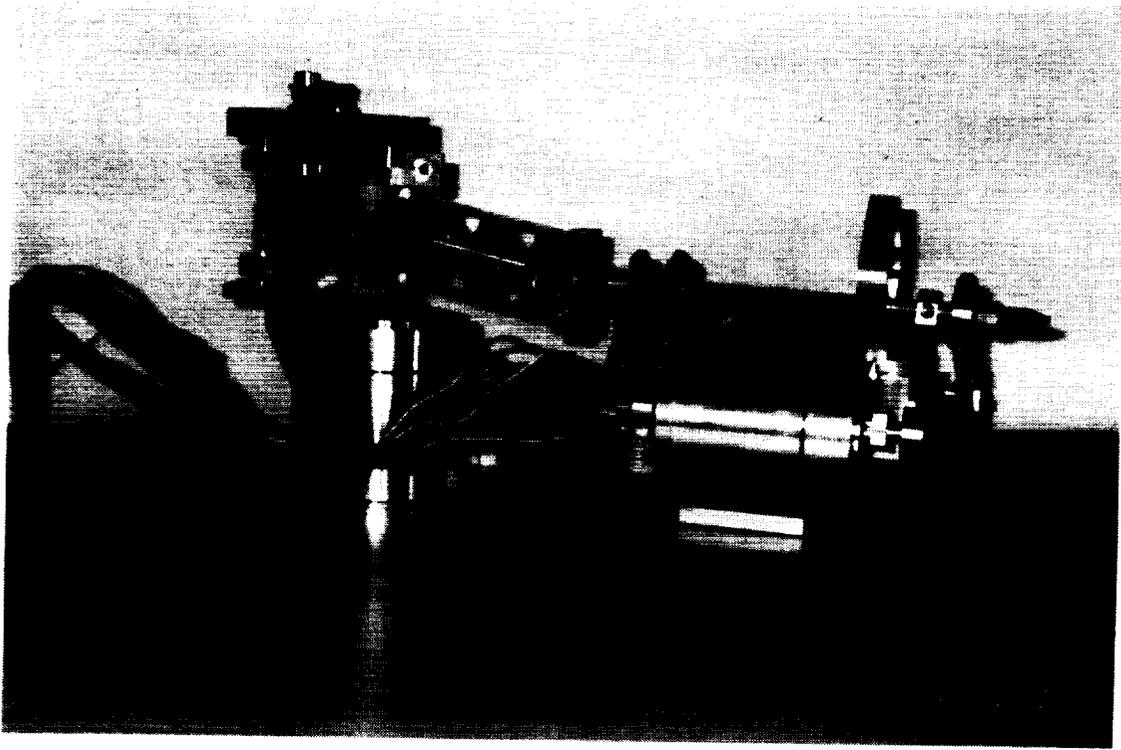
The computational complexity problem has been addresses by building a high-performance real-time cost-effective multiprocessor system. This system is highly modular in structure, and was designed to support the needs of advanced robotic systems. The robot mechanism uses a macro-micro design, which allows the end-effector to have the properties of a small and light robot, yet preserves the workspace capability of a large robot. The following section discusses the mechanism design, and section 2.0 discusses the controller.

1.0 A Force Controllable Manipulator

A manipulator capable of delicate interactions with its environment must be designed differently from today's position controlled robots. It has been shown that a high-bandwidth, low effective end-effector inertia design is helpful for precise force control [1,2]. There are two design approaches to creating such a structure. One is to design the manipulator so that the entire structure is very light. This approach can be very costly since expensive materials and tight tolerances are required. The other approach is to attach a low-inertia small manipulator to the end of another larger and heavier manipulator. This macro-micro structure results in a combined structure with the low end-effector inertia of the micro robot and the large workspace of the macro robot.

The macro-micro design couples a 3 degree of freedom micro robot to the end of a 5 degree of freedom macro robot. A schematic and photograph of the micro design is shown in Figure 1, and a schematic of the macro design is shown in Figure 2. For the micro robot, the x and y directions are actuated with a parallel set of 5-bar-link mechanisms, one attached to each side end of the two motor shafts. The z motion is actuated by a fixed motor oriented perpendicular to the x and y motors. This motor is attached to the parallel link mechanism through a pair of universal joints. The range of motion is 2 centimeters along each axis. A fourth pneumatic motor, located

furthest from the tip, rotates the tip through a series of transmissions at a constant speed for polishing, finishing, and grinding applications.



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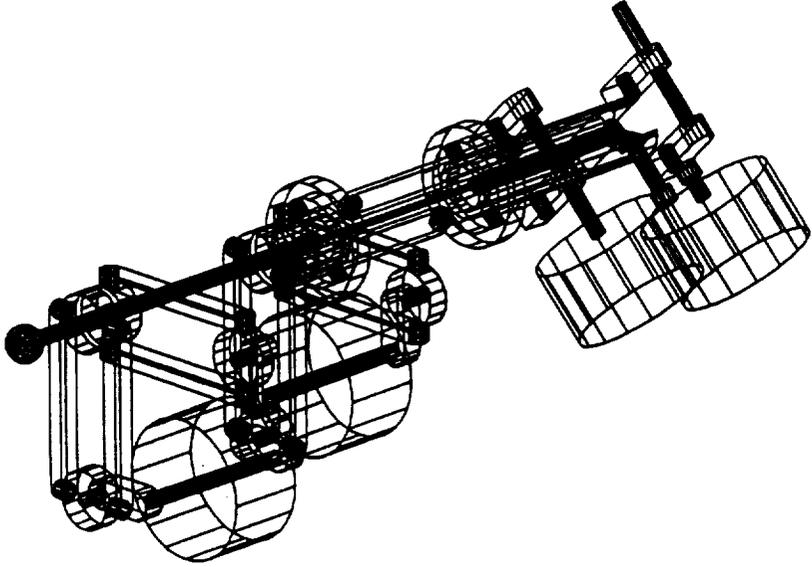


Figure 1. The Micro Manipulator

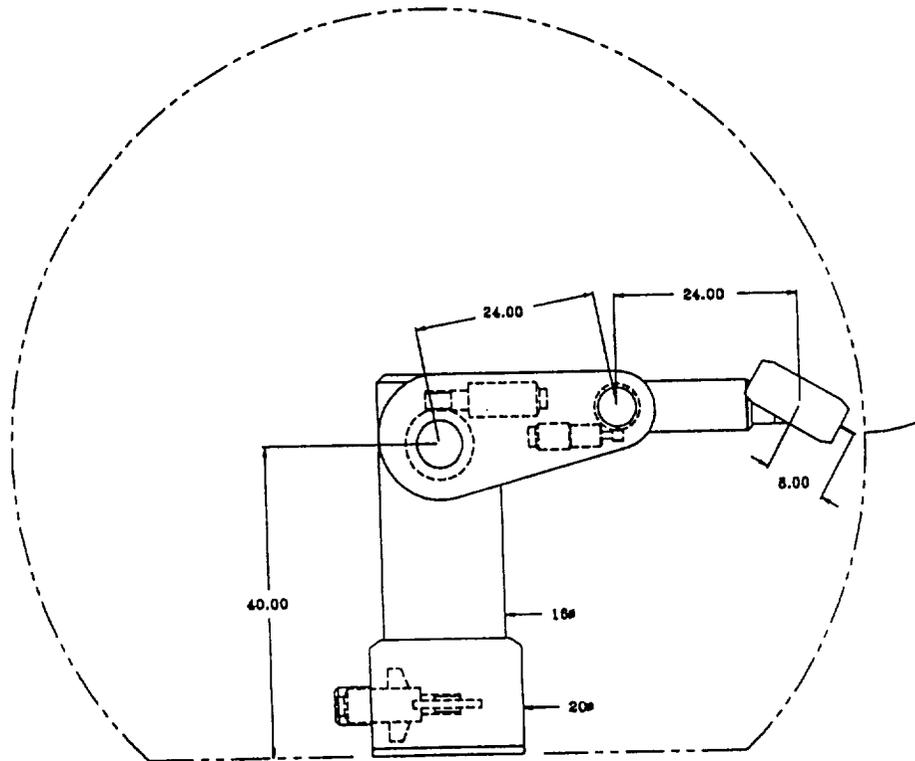


Figure 2. The Macro Manipulator

Since the macro and micro robots coordinate as a single system, many tradeoffs influence both designs. For example, the size of the micro robot's workspace influences the accuracy with which the macro robot must be able to position itself. The mass of the micro robot also influences the payload capability of the macro design. Our design strategy was to simplify the macro design by making the micro robot more capable. The main consequence of this decision is a large micro workspace, thereby allowing less accuracy and performance in the macro. However, the micro's workspace volume directly influences the overall mass and size of the design considerably. In our design, reducing travel along each dimension by a factor of two roughly reduces the size and mass of the micro robot by a factor of two.

The main objectives of the micro design were to minimize end-effector inertia, minimize joint friction, maintain tip orientation throughout the workspace, and support a maximum payload (i.e. force exertion) of 3 kilograms. The resulting tip inertia is roughly 250 gms. The joint friction was minimized by using direct-drive transmission and limited angle flex bearings at the joints. These limited-angle bearings offer virtually no friction. They do generate a spring force, however, which must be compensated for in the control law. Tip orientation is maintained by the parallel 5 bar link structure.

Secondary goals were to minimize the size and weight of the micro-manipulator. The final size is 35.5 by 19 by 17.8 centimeters, and the weight is 6.3 kilograms. Strain gages mounted on the links provide sensing for 5 degrees of freedom (as shown in Figure 1). Sensors for detecting a moment about the tip axis were not included.

The macro design is a 5 degree-of-freedom articulated manipulator, as shown in Figure 2. This manipulator supports the weight and continuous force exertion capability of the micro-manipulator throughout the workspace with 1g acceleration. A 1 meter reach was chosen as a reasonable workspace. The main features of this design are high mechanical rigidity, simple kinematics, large workspace volume, and cost effectiveness.

The 5 degree of freedom kinematic structure is very similar to the first five joints of a PUMA robot [3]. A 6th joint is unnecessary because the tip of the micro robot spins continuously. Link offsets, link lengths, and structural characteristics were designed to account for the size and mass constraints imposed by the micro-manipulator, however.

A variety of actuation methods have been considered. The options that were considered were direct-drive, harmonic drive, spur gear, worm gear, planetary gear, and different combinations of these. The goal was to maximize accuracy, resolution, and stiffness while staying cost effective. After various optimization procedures we decided on a harmonic drive - worm gear double reduction scheme for the first three joints. The last two joints, which carry a much smaller load, use harmonic drives.

The procedure for solving for the inverse kinematics equations of this robot is very similar to that of the PUMA robot and can be found in many of different robotics textbooks [4]. The kinematics and dynamic equations used for computed torque control can also be derived very easily using of the generalized formulations which have been developed [5]. However, because of the high reduction ratios of the transmissions, independent joint control is adequate.

2.0 A Modular Multi-processor Control System

A high performance multiprocessor system is used to satisfy the significant computational demands of controlling this robot. We designed this control system as a general purpose high performance controller with both hardware and software modularity as a key feature. The ability to easily rearrange and extend hardware and software modules to support different requirements for various tasks is particularly important in experimental projects such as this. Frequently designs are unable to accomodate even minor modifications without a major impact to the existing system configuration.

A schematic of the motion control system configuration is shown in Figure 5. The four basic units are the compute unit, the global memory unit, the position, velocity and digital I/O unit, and the A-to-D D-to-A unit.

The compute unit is based on Texas Instrument's TMS320C31 floating-point digital signal processor. In our earlier generation systems [6,7], we used a novel 3D computing processor which proved to offer much higher performance than DSPs or RISC processors on kinematic and dynamic calculations. However, due to the high cost of implementing this design using discrete datapath parts we opted to use an off-the-shelf processor. At a crystal speed of 33Mhz the TMS320C31 offers 33 MFLOPS of peak power. Each unit contains 2 Mbyte of program memory, 2 Mbyte of data memory, 2 programmable timers, interrupt capabilities for both the I/O Bus and the VME bus, and bus arbitration logic for accessing the I/O Bus. The memory is directly accessible by the host computer over the VME bus. Different levels of concurrency is provided to maximize execution speed. For example, the host may access data memory while the processor continues program execution. Programs are developed in either C or C++ on the host computer and downloaded to the appropriate unit before run time. Several libraries are provided to support program development. Remote procedure calls were provided so that UNIX services, such as printf(), scanf(), open(), and close(), are available for code development. Math functions, functions for accessing sensory data, and message passing functions for multi-processing are also provided.

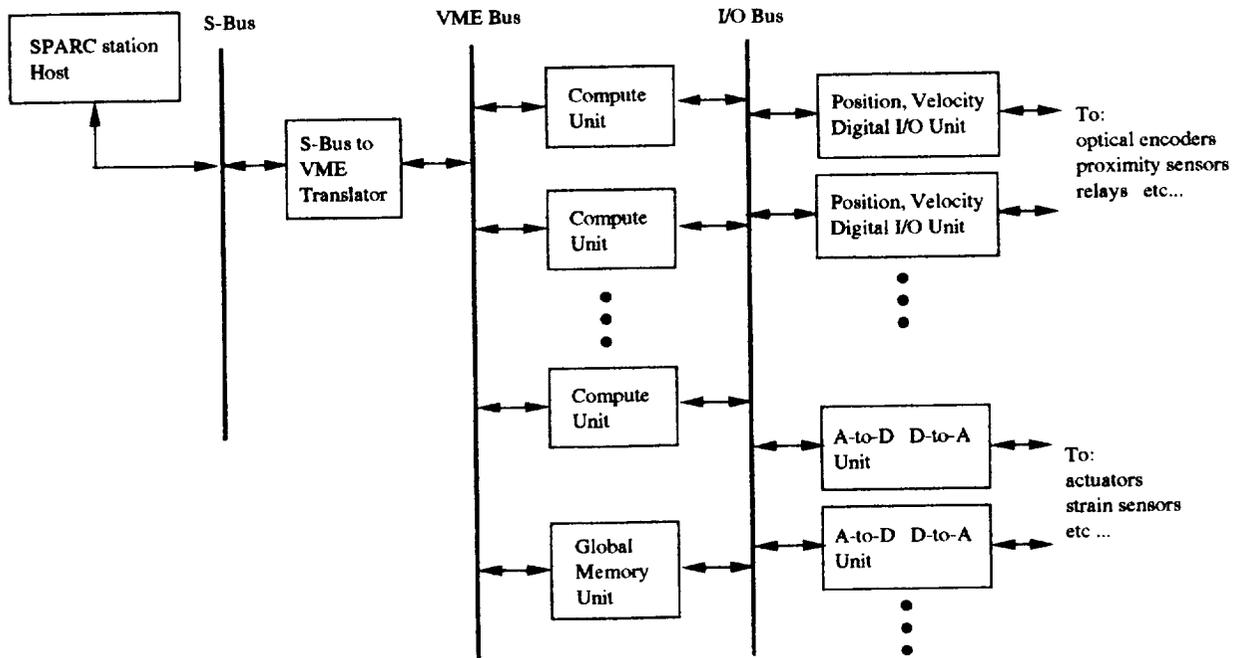


Figure 5. The Motion Control System

The global memory unit contains 2 Mbytes of memory for passing messages between compute units, to and from the host, and to store global variables shared by multiple compute units. A mailbox message passing scheme is implemented to support multiprocessor communication. Information is passed from one compute unit to another compute by first acquiring the IO Bus, then writing the message into the target compute unit's mailbox, and then interrupting the target compute unit. The target compute unit reads its mailbox, and sends an acknowledgement to the sending compute unit. Hardware interlocking and interrupt mechanisms are included to achieve high bandwidth communication. Reading or writing a message requires ~3 ms overhead and another 180ns for each 32-bit word.

The position, velocity, and digital I/O unit accepts 6 channels of 2 channel quadrature encoder input and translates that into absolute position and velocity. Each channel also supports index pulse detection, which is generally used for position homing. Position is stored to 24-bit accuracy and velocity is stored to 10-bit accuracy. Thirty-two bits of digital input and 32 bits of digital output are included for instrumenting relays, proximity sensors, or other on-off type devices.

Velocity is generated by two different schemes, depending on the velocity range. At low speeds, velocity is generated in hardware by a free running counter which measures time between successive encoder counts. At high

speeds, velocity is determined by calculating the number of encoder counts which have passed during the previous sample period. For each velocity read operation, the software automatically chooses between the two schemes by reading the velocity counter and comparing it with a threshold value. The result of this method is a more accurate velocity signal with minimized quantization effects.

Velocity is generated in hardware from the optical encoder signal by incorporating a free running counter chip which calculates the time between successive encoder pulses. Velocity is usually derived from a quadrature signal by subtracting the current position with the previous sample period's position. This subtraction may result in very quantized velocity signals especially at high sample rates, however. The hardware counter method produces a much more finely resolved velocity signal. There is still a problem, however, since at low speeds there may be significant time delay between new velocity acquisitions.

The A-to-D D-to-A unit provides 9 channels of 12-bit digital-to-analog output, and 8 channels of 12-bit analog-to-digital input. Separate digital to analog converters are provided for each output channel. A single analog-to-digital converter is multiplexed between the 8 input channels. Each channel requires 3 ms of conversion time. Software routines are provided to configure the card to only sample the channels which are in use. Conversion is performed continuously and asynchronously only on the channels being used. Therefore, the maximum delay from when the data was acquired to when it was read is $3 \text{ ms} \times \text{number of selected channels}$.

The software structure of the operating system level software is shown in Figure 6. Note that there is a clear separation between the real-time execution environment and the non-real-time UNIX environment. The UNIX environment is used for program development, user interface, and monitoring the real-time system. Because of the UNIX front-end, the robot interface must be carefully constructed such that the integrity of the real-time system is not lost. For example, UNIX service requests by the real-time system cannot be made while servoing since a real-time response from the UNIX process cannot be guaranteed.

Figure 7 shows the general hierarchy of the application software of the system. Macro calls provide fast access to the various hardware features of the system. C language routines provide the next layer, which support functions such as synchronizing multiple processes, remote procedure calls to the host, and algorithms for performing mathematic operations. At the highest level, object-oriented class libraries are supported in C++.

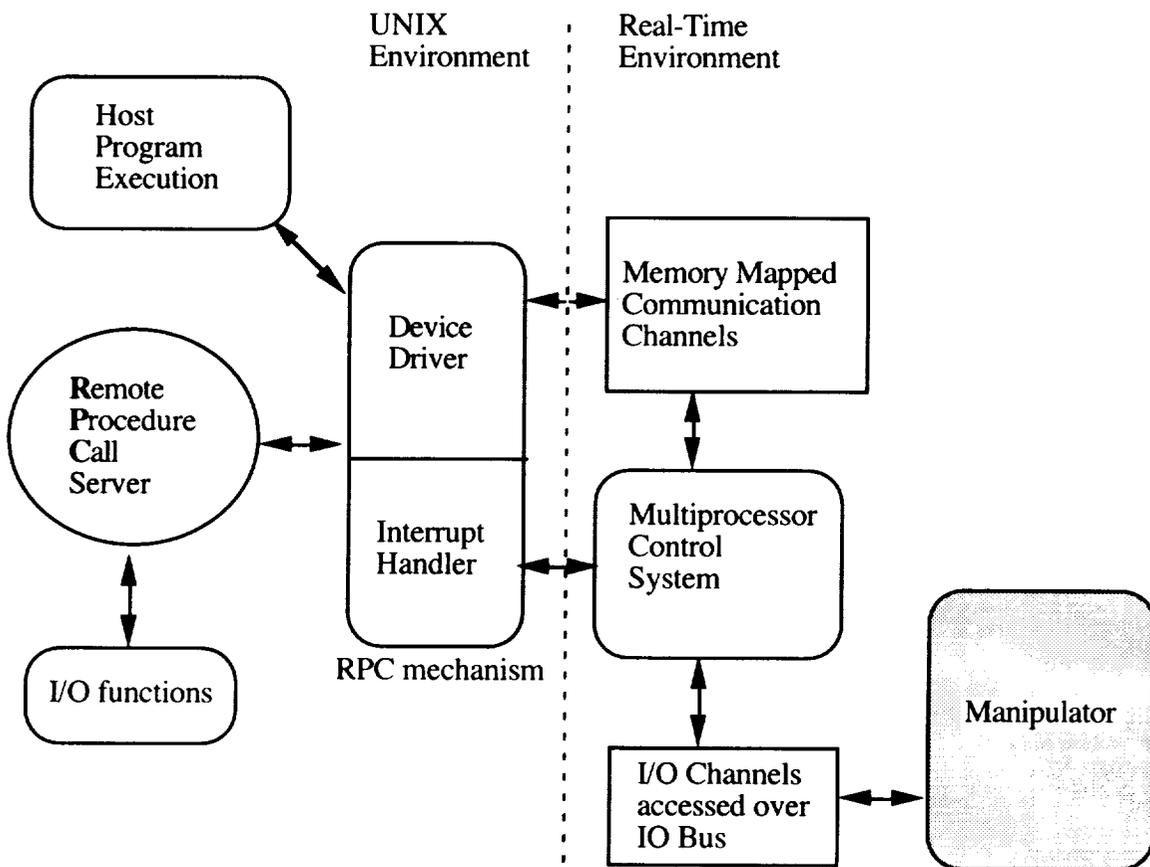


Figure 6. System Software Structure

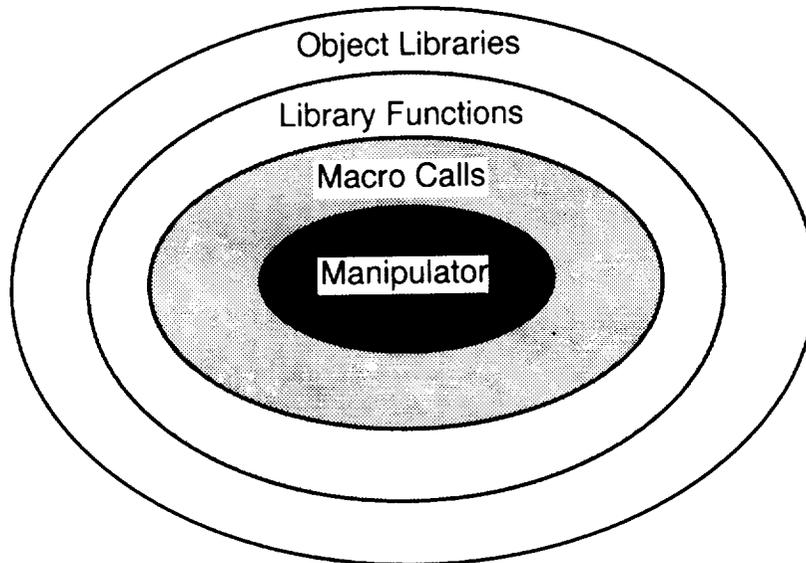


Figure 7. Software Support for Application Development

3.0 Impedance Control for a Macro-Micro Robot

The impedance control method enables a robot to interact with its environment in a well controlled and precise manner [8]. The manipulator's end-effector reacts to environmental disturbances in the same manner as a linear mass, spring, damper system. The mass, spring, and damper values are controlled electronically and can be different along different axes, and can continuously change during a trajectory.

This method is different from hybrid position/force control [9] since specific forces or positions are never specified. The control variable is the equilibrium point of the mass, spring, damper system without external forces. The advantage of this methodology is that a single control variable and control algorithm can be used to guide a robot through interactions with the environment. Hybrid position/force control, on the other hand, requires a switch in control methods and control variables whenever the robot changes the configuration in which it interacts with its environment.

Figure 8 gives an example of a trajectory specified by the equilibrium path where the manipulator comes into contact with a surface, slides across it, and then leaves the surface. Note that the nominal force exerted on the surface is proportional to the spring constant. By using the spring constant and surface location information, it is simple to calculate the equilibrium point's trajectory to produce a desired force across the surface. The force at the contact point will be influenced by contributions due to the mass and damper as well. Consequently, if precise force control is important, the smaller the mass and damper values are the better. The macro-micro design facilitates small mass values.

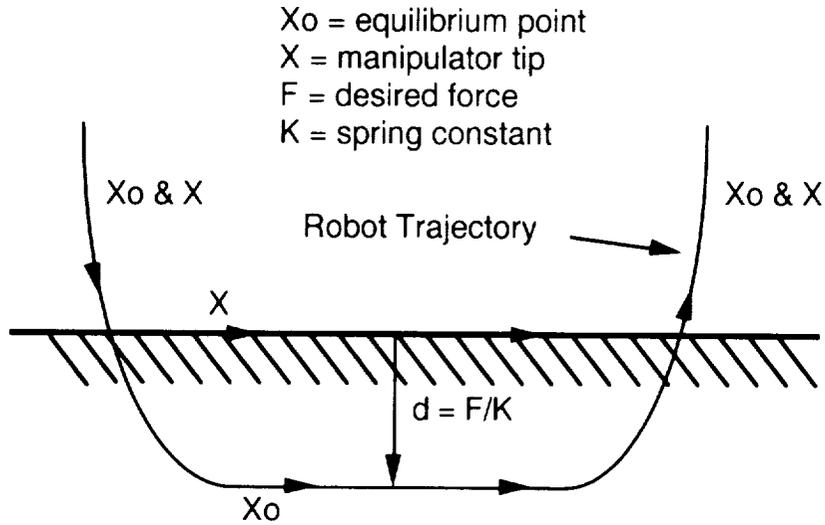


Figure 8. Manipulator trajectory specified by equilibrium point

The impedance equation can be written as follows:

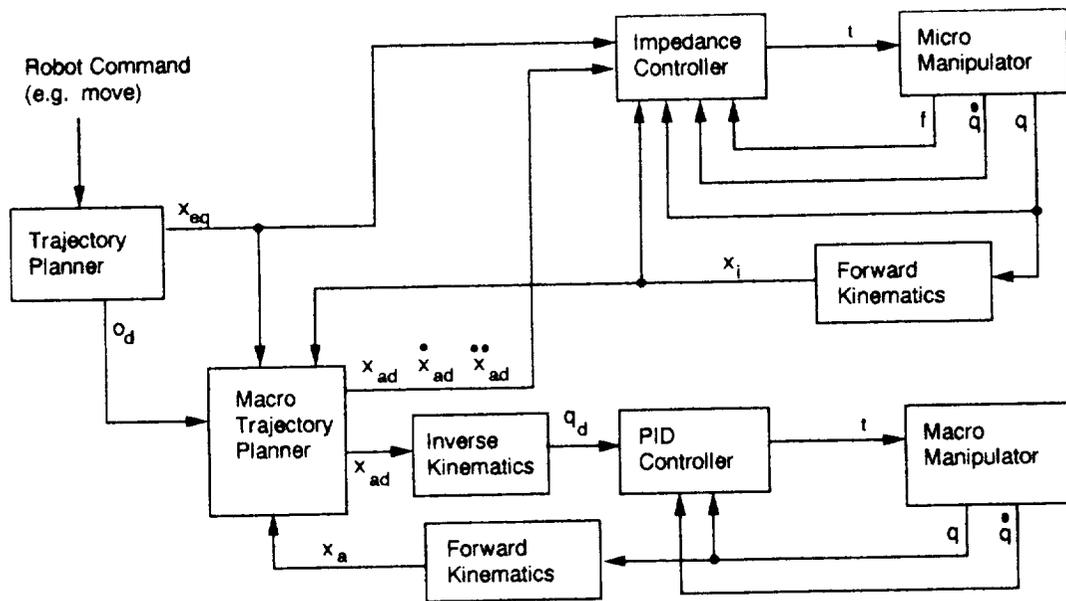
$$F_{\text{ext}} = M_s (\ddot{X}_R - \ddot{X}_0) + C_s (\dot{X}_R - \dot{X}_0) + K_s (X_R - X_0)$$

where

- F_{ext} external force applied to robot tip
- X_R tip position of macro-micro robot
- X_0 desired equilibrium point of macro-micro robot
- M_s desired mass constant
- C_s desired damper constant
- K_s desired spring constant

Impedance control of a macro-micro design has the added complexity of managing the manipulator's redundancy to optimize force interactions by exploiting the micro robot's low tip inertia. In other words, the redundancy should be used to keep the micro robot from reaching its workspace limit, where one or more degrees of freedom would be lost. Our robot has 3 degrees of redundancy along the translational axes. Delicate interactions for translational motion is possible because of the micro robot. Orientation is left to the macro robot and is position controlled.

A block diagram of the control structure is shown in Figure 9. The impedance control law, which outputs torques to the micro robot, is derived by combining the desired impedance equation stated above with the equations of motion of the micro robot presented in section 1.2. Note that the servo control law for all 5 joints of the macro robot is a simple position controller without feedback from the micro robot. However, feedback from the micro robot is input into a real-time trajectory generator for the macro robot. This trajectory generator uses the robot's redundant degrees of freedom by constantly updating the macro robot's desired position such that the micro robot is centered in its workspace, and hence far from its workspace boundary. Consequently, entire manipulator can respond to external disturbances with the quick reaction of the micro robot over the entire workspace of the macro robot.



- x_i - micro robot's actual tip position
- f - micro robot's force sensor readings
- x_a - macro robot's actual tip position
- o_d - desired orientation of macro-micro robot
- $x_{ad} \dot{x}_{ad} \ddot{x}_{ad}$ - desired tip position, velocity, and acceleration of macro robot
- q_d - desired joint position
- x_{eq} - equilibrium point
- q - actual joint position
- \dot{q} - actual joint velocity
- t - torque

Figure 9. Impedance control of macro-micro robot

The maximum distance which the micro will deviate from its center position is a relationship which includes the ratio of the maximum accelerations of the macro and micro, the magnitude and time of the maximum disturbance, and the reaction time of the servoing system. This information is important since it quantifies the critical tradeoffs between the micro's performance versus the macro's performance. We will obtain more insight into these relationships through experimentation of the robot.

With this control strategy, since the macro robot is purely position controlled it may be possible to apply this strategy to a micro connected onto the end of a commercial robot. However, the success of this approach is dependant upon the ability of the commercial robot to accept and quickly respond to new position commands. The requirements of a commercial robot used in this manner will become clearer with more experimentation on our robot.

5.0 Conclusion

An 8 degree of freedom macro-micro manipulator is controlled by an impedance-based controller, executed on a high performance multiprocessor control system. The manipulator's tip inertia is very low and can therefore react quickly to force disturbances. The control method compensates for manipulator dynamics, and can generate very precise torques. The multiprocessor offers sufficient compute power to meet the real-time demands of the control strategy.

Preliminary results show that this design will be capable of precise force control. More conclusive experimental results will be available at the end of the research effort in 1993.

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