The Concept and Implementation of a Passive Trajectory Enhancing Robot

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Abstract

A novel controlled passive device is described which allows its end effector to be pushed only along a specified but arbitrary path. The force to move the end effector must be provided by an external source such as a human, gravity, or fluid flow. Possible applications include computer assisted surgery, haptic displays, exercise machines, and teleoperator masters. Advantages of the passive approach taken include safety from run away motors and freedom from supplying substantial amounts of energy to the device. This paper describes the concept and how it has been implemented and shows feasibility through initial experiments with simple control of a prototype system.

1. Introduction

The Passive Trajectory Enhancing Robot (P-TER) is a multi-degree of freedom mechanism designed to guide the motion of its end effector along a desired programmed path while it is pushed by a human or other source of energy. The joints of the mechanism are equipped with controlled clutches that are actuated by a computer in response to the applied force, joint positions, and velocities. Some of the clutches have one shaft attached to ground, resulting in a brake. The actuated clutch produces joint torques that can only resist relative motion between the two points of mechanical attachment to the mechanism. By selectively coupling two points on the mechanism, the motion of the linkage under applied forces can be directed to follow a programmed path with controlled speed. The research under way is exploring the capabilities and limitations of such a device and the most appropriate mechanism design and control algorithms. The purpose of this paper is to describe the concept, its advantages, one implementation of the concept and preliminary results from simple control applied to the device.

P-TER inherits its missions from several devices that precede it. Manipulator arms have primarily been used to move under computer direction as a robot or under remote human direction as a teleoperated slave. Haptic interfaces can closely resemble robotic arms, and have the function of displaying information to a user via force-velocity relationships. Passive mechanical linkages such as four-bar linkages or slider-cranks function to direct an external force source along a constrained path. It may be possible for P-TER to satisfy some of the needs for these devices with the advantage that no external power source (except for control signals) need be supplied. An inherent safety advantage results from the arm being passive, since a malfunction can never initiate motion that might injure nearby humans. The safety may have advantages for any device that, as part of its function, must interface with a human being and be capable of exerting considerable force.

P-TER interacts with a source of energy. In most of the applications of current interest that source is a human user. It could however, be a potential field (gravity) or a stream of fluid in motion. As a passive device, P-TER is unable to supply energy to the environment it interacts with. In its present form the device is also unable to store energy except as kinetic energy as a consequence of the linkage motion. P-TER dissipates energy and transfers energy instantaneously between degrees of freedom. To be passive at the point of interaction with the source, the source applied force vector f_S and the source velocity vector v_S must have the relationship to each other that

$$f_S^T v_S = P_S \geq 0 \qquad (1)$$

To influence the trajectory of the source, P-TER must facilitate motions in some directions and impede motion in other directions. This is done by coupling the axes of the mechanism to the stationary base or to each other by controlled passive resistances. These resistances could be electromechanical clutches (brakes) or fluid valves. A physical consequence of passivity is that the joint torque vector τ and resulting joint motion ω are also passive, absorbing energy as calculated by

$$\tau^T \omega = P_J \leq 0 \qquad (2)$$

The difference between P_J and P_S is the kinetic and potential energy stored in the mechanism. Actively powered robots commonly perform tasks where the end effector motion absorbs energy, so condition (1) is satisfied. As they are constructed, however, condition (2) is not necessarily met.

The structure of this paper is as follows. Some passive controlled devices appearing in the literature are briefly described. Next the concepts employed in designing this device are explained. Then a description of the current design implementation of this device is given and preliminary control algorithm that has been applied with representative results is given. Some of the great amount of future work needed is then presented.

2. Previous Work In Controlled Passive Devices

Several authors have described controlled passive devices, very recently passive devices for following specified trajectories have been reported. The device in this paper, P-TER is described in more detail and with other studies of its behavior in Charles, 1994 and Davis, 1996. Other authors have described partially passive devices for positioning. Arai and Tachi, 1993 describe a two degree of freedom serial link manipulator using only a brake to control the second joint. The first link is moved by a motor. Li and Horowitz, 1995, describe a control scheme for returning a robot arm to a path using the concept of a velocity field. The cited paper does not describe a passive device and present results on an active, not a passive device. Colgate, Peshkin, and Wannasuphoprasit, 1996 and Peshkin, Colgate, and Moore, 1996 describe a very different implementation of a similar concept where coupling is based on a continuously variable transmission instead of an inherently dissipative coupling of axes. Other research in passive devices seek to impart a desired mechanical impedance rather than achieve a desired trajectory or path. An example is the controlled remote center of compliance device.

3. Concepts Employed

The limitations of the simplest passive devices will now be described in an effort to explain the rationale for the design implemented. Why is it not sufficient to take an existing arm design and replace the motors with clutches? This is perhaps best illustrated with a specific example arm: a two link prismatic joint design with perpendicular axes of motion. The two translations permitted by the joints are perpendicular. A brake at each joint can provide a resistive force upon any motion of that joint. We will assume for the moment that inertial forces are negligible, or at least equal for the two directions of motion. If a force is applied in a given direction, equal resistance to motion at the joints would result in motion exactly in the direction of the applied force. If the x-axis clutch were providing more resistance to motion, however, and an angle α between the direction of the force and velocity would result. This is similar to the preliminary control implemented below. The limitation of this design is apparent when the direction of applied force is slightly to one side of an axis and the desired velocity is to the other side. In this case even a slight correction would require joint velocities and forces to be of the same sign, a violation of the passivity of the joint.

A modification that avoids the above severe limitation includes two controlled resistive couplings between the two axes. The two couplings have the opposite relative directions during a given motion. When one or the other of these couplings is locked so that no relative motion occurs between the braking surfaces, the motion of the source will be at an angle of plus or minus 45 degrees to x and y axes. Mechanical design to practically implement these couplings is difficult, especially for multiple degrees of freedom. The design of P-TER, one device that can achieve this goal, will now be described.

4. Description of P-TER:

P-TER is a controlled five-bar linkage system as shown in Fig. 1. A human user moves the device through the end effector. The end effector of the linkage consists of a handle-mounted force gauge The gauge measures force components along and normal to Link 4. Rolling element bearings in the handle prevent the application of significant torque while the force gauge remains fixed relative to the final link. The force measurements are crucial in determining the control of the device.

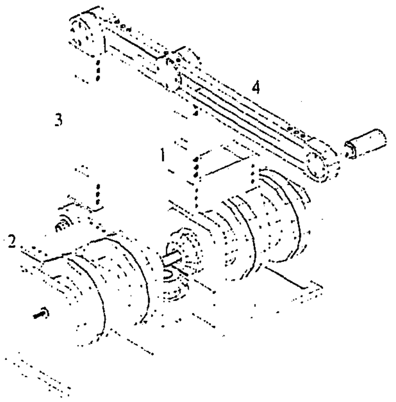

Fig. 1: The Passive Trajectory Enhancing Robot P-TER

The primary links labeled "1" and "2" in Fig. 1 have a coincident, stationary axis of rotation, which enables the control mechanism that was selected. The control mechanism can be described as a superposition of two separate devices as shown in Fig. 2 and Fig. 3. Fig. 2 depicts the two primary links connected to each other through two shafts coupled by a clutch. The clutch can be controlled to couple or release the shafts as appropriate for transferring energy between the links. Termed "direct coupling," this action would tend to make the two links rotate in the same direction. In addition to the clutch a brake is mounted to each link for the purpose of slowing the link down, thereby removing energy from the system.

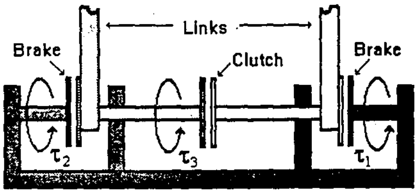

Fig.2: Direct joint coupling mechanism

The second device shown in Fig. 3 is nearly the same as the first, with the exception of the bevel gear differential placed between the two links. In this mechanism, engaging the clutch will tend to force the links to rotate in opposite directions. This action is termed "inverting coupling."

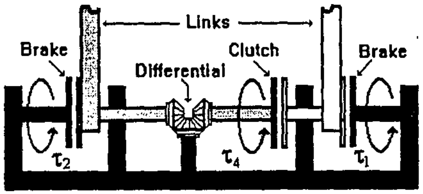

Fig. 3: Inverting joint coupling mechanism

P-TER is a superposition of these two mechanisms. The direct coupling is achieved through a solid shaft running between the primary links. Link 1 is permanently attached to the solid shaft, and can be coupled to Link 2 through an electro-magnetic clutch. Inverting coupling is handled by a pair of hollow half-shafts concentric to the direct coupling solid shaft. The concentric half-shafts are connected through a bevel gear differential. Link 2 is permanently attached to one of the half-shafts, causing both half-shafts to rotate with the link. As before, Link 1 can be coupled to the second half shaft through a second electromagnetic clutch.

The link lengths have been chosen to simplify the equations of motion for the device. All terms dependent on the cross-product of the two joint velocities have been eliminated. An additional benefit is that all motion control devices are mounted at the stationary axis of rotation, eliminating the need to translate them with the linkage. By orienting P-TER for motion in a horizontal plane, gravity effects are eliminated.

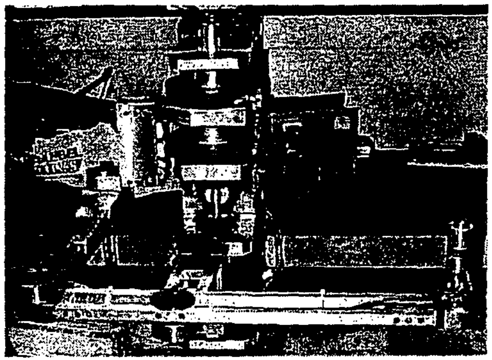

Fig. 4: Re-oriented P-TER

The arrangement of sensors, actuators, controllers and their interface to the mechanical device is shown schematically in Fig. 5. PTER is equipped with sensors to measure the joint position of each of the primary joints, and a force sensor to measure the force input at the end-effector. The joint sensors are potentiometers mounted to each shaft. The force signal is obtained from strain gauge readings at the end effector. The strain values yield the corresponding force parallel and perpendicular to the link in the plane of motion, i.e., Cartesian coordinates at the tip. These values can then be transformed to yield the corresponding global Cartesian components of the force.

The joint sensor resolution is approximately +/- 0.001 radians, which translates to about 0.05 inches at the end effector. Force sensor resolution is approximately +/- 0.025 lb., with the maximum readable force being 50 lb. in either of the primary directions.

The joint position signals are numerically differentiated to yield joint velocities. Numerical differentiation of a sampled signal adds a great deal of noise to the signal. Digital low pass filters have been implemented to attenuate most of this added noise, yielding a useful signal for the joint velocity.

The physical test bed is interfaced to a PC via analog-to-digital (A/D) and digital-to-analog (D/A) converters. The PC has a 486 processor operating at 50Mhz and runs under the DOS operating system. The PC is equipped with an eight-channel, 12-bit A/D Converter, and a four-channel, 12-bit D/A converter. We use four input channels, two each for the components of joint position and end effector force, and four output channels, one for each of the electromagnetic clutches. Each clutch has a dedicated amplifier/power supply to provide the current necessary to drive the clutch. The code for interface with and control of P-TER is written in the Object Oriented programming language, C++.

The electromagnetic clutches are the primary control devices for the robot. The clutches are controlled by a variable input current. The attractive force between the plates of the clutch is proportional to the current through its field coil. The clutch can therefore provide a controlled, variable resistance torque to the links of the manipulator. Each clutch has been calibrated to correlate control currents with resulting joint torques.

With respect to real-time control, the bandwidth of the clutches' is a significant constraint. Initially, there is a short time interval needed for the control signal to reach the clutch from the PC. More significantly, we must be concerned with the time required for the current in the clutch coil to build up, (electrical time constant), and the time required for the clutch to build up to the commanded torque (mechanical time constant). The most limiting is the mechanical time constant which can not be directly measured in our laboratory. However, the manufacturer reports a time of 0.124 seconds to build up to 80% of the rated torque. Preliminary experiments indicate that this is indeed a reasonable estimate.

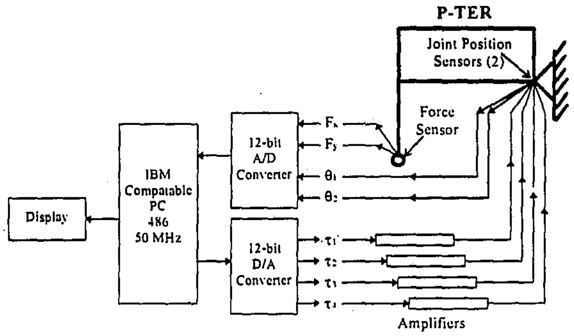

Fig. 5: Schematic of Components in P-TER

5. Preliminary Control Experiments

A very crude position control algorithm for P-TER has been implemented. This method uses only the position data from the potentiometers at the joints, and force data from the strain gages in the force transducer at the handle. This approach also entirely ignores the dynamics of the system and only makes use of the kinematics of the device, i.e. one can model the system as if the system has no mass. Neglecting the equations of motion for the system was justified for this first try at control since at very low accelerations the dynamics have very little effect on the device's motion. Under these assumptions the end-point will move in the direction of net applied force. We further restrict use of the actuators to permit only braking; the coupling clutches are not used. A simple but representative test path is chosen, that being a circle centered at the fixed axes of links 1 and 2.

In summary the approach of the simple control algorithm are:

- use position data and force data
- ignore the dynamics of the system
- use only the two brakes to ground
- follow smooth paths such as a circle with center at the base joint axis.

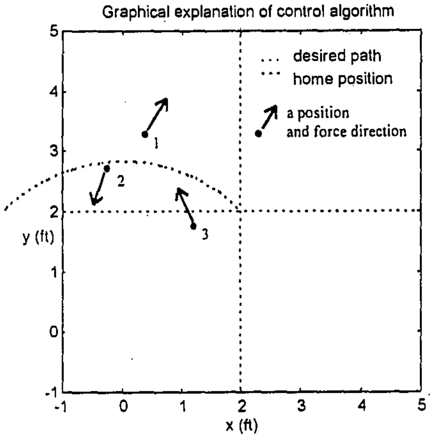

Fig. 6: Significant positions and forces relative to path.

A graphical description the control algorithm is given in Fig. 6 as explained in the remainder of this section. Control is based on a corridor of acceptable positions surrounding the ideal path. The user applied force tends to rotate the joints so that position error is either increased or decreased. Rotation that is predicted based on statics which will reduce this error is always permitted. Inside the corridor rotation is also always permitted. Outside the corridor however, rotation that increases the position error is restricted by locking the brakes. Note that only position and force measurements are required.

Three specific cases shown on the plot:

1. don't allow motion that will bring the point further away
2. no control required, any force direction is ok inside the corridor
3. no control required, the force is bringing the point back inside the corridor

The actions in these rules can be implemented with an algorithm such as the following.

6. Test Results

Fig. 7 shows the actual and desired path as viewed from above. Arrows show the direction of the force on the end-point of P-TER with the length of the arrow representing the relative magnitude of the force. The source of the force is the experimenter pushing the handle by hand. As can be seen, the motion is not smooth, but it shows the potential for path control of this passive system even with a very simple control algorithm.

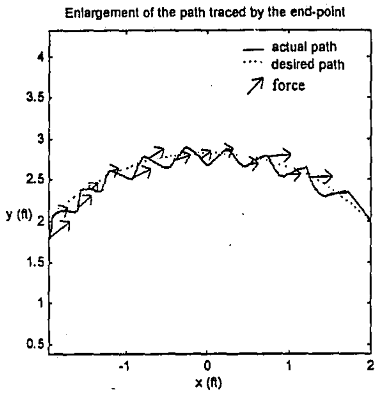

Fig. 7: Path and force vectors for the "on-off" control algorithm

Fig. 8 shows the results of the next control algorithm implemented. This algorithm is simply a modification of the "on-off" control previously described. Instead of locking up the brakes when the position error is beyond some boundary, the magnitude of the brake excitation increases as the position error decreases. This control algorithm resulted in a much smoother path.

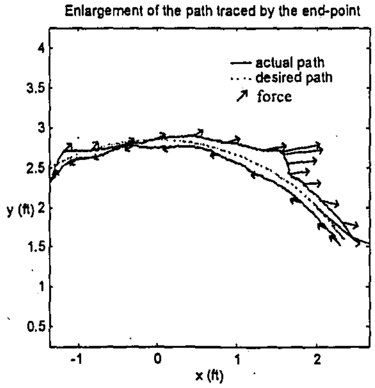

Fig. 8: Path and force vectors for the "on-off" control algorithm

7. Future Work

Many questions remain to be answered about the potential of passive trajectory enhancement and better ways to implement it for various applications. Current efforts to better understand the system dynamics will enable research to proceed through simulations, analysis and experiment.

Work on the preliminary rule based algorithm will continue. The use of the coupling clutches for control will be investigated and eventually a control algorithm will be developed which uses all four energy dissipating devices to provide improved control of this system.

Means of mapping from the torques commanded by conventional control schemes to realizable torques are also being considered.

While applications in several domains have been alluded to, the use of P-TER as a haptic display for virtual reality is the initial application domain under investigation. The ability to realistically display a maze with solid walls will be considered. A fully active device with identical kinematics and workspace is available for comparison to active haptic displays.

Finally, many alternative mechanical devices could be constructed with the same principles of energy sharing between axes. By experimenting with one available example, future designs might be improved.

8. Acknowledgments

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