Torque Control of a Redundantly Actuated Passive Manipulator

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Abstract

The study of passivity in the robotics domain has been motivated by safety and stability concerns in applications such as haptic displays, surgical robots, teleoperation, and manufacturing. This paper describes a passive manipulator with a redundant actuation scheme which allows for enhanced control capabilities and greater overall utility. An algorithm for determining passive actuator excitations from generally active control laws is presented. The *torque translation* algorithm is a graphical method based upon using knowledge of the specific passivity-induced constraints to select a subset of the available actuators to provide an acceptable output torque. The algorithm successfully provides a set of passive actuator torques for all manipulator states, and experimental results are given.

1. Introduction

Many robotic applications, including haptic interfaces, surgical robots, and mechanical devices for exercise and rehabilitation, involve substantial interaction between the robotic manipulators and humans. The issue of safety, especially in health care applications, is of utmost concern. One commonly used approach to the issue of safety is the incorporation of redundant safety features and extensive testing before use. However, this does not remove the possibility of error and ensuing harm to nearby humans. An alternative approach is to remove the power-supplying components, such as electric motors or hydraulic cylinders, altogether.

In this work, investigation is made of a device made up entirely of *passive* components. By definition, passivity requires that the device do no positive work on its environment. Therefore, the passive components can not generate arbitrary forces or motions, but may be able to modify forces or motions provided by an external source, such as a human user, to produce passively controlled forces and motions.

The Passive Trajectory Enhancing Robot, P-TER, is a mechanically passive, two degree-of-freedom device developed at the Georgia Institute of Technology's Intelligent Machine Dynamics Laboratory[1]. It was designed to guide the motion of its end effector along a programmable path, given an arbitrary input force. The input force is presumably that of a human user using the manipulator to perform some task. The joints of the mechanism are equipped with controlled brakes and clutches that are actuated by a computer in response to the applied force, joint positions, and velocities. The brakes act to independently remove energy from the individual degrees of freedom while the clutches, however, act to transfer energy *between* the degrees of freedom, resulting in enhanced control capabilities.

Each clutch used for the control of P-TER is considered to be a passive actuator. Since the number of actuators is greater than the number of degrees of freedom, P-TER is said to be a *redundantly actuated passive manipulator*. Two critical implementation issues arise in the control of such a device: 1.) How are (generally active) control algorithms implemented on a passive device? and 2.) How are the excitations for each of the actuators determined?

This paper reports the formulation of a *torque translation* algorithm which translates the commands of an active torque-based control algorithm into suitable actuator commands for a redundantly actuated passive manipulator. The algorithm is based on exploiting the known limitations of the full set of passive actuators to determine a subset of actuators which is most capable of producing the required torque. The capabilities of the passive actuators are in general dependent upon the instantaneous states of the manipulator.

2. Passive Robotics

The issue of passivity comes up in several research areas. The use of passive systems in medical tasks offers a potentially higher level of safety. In more traditional robotics and control domains, the issue is often stability. It has been suggested that passivity of the manipulator can guarantee stability in tasks which require stable dynamic interaction with their environments.

Goswami and Peshkin introduced the topic of passive robotics in the context of mechanical computation [3]. The mechanical device, or manipulator, computes a particular motion in response to a particular forcing. This relationship between force and motion, the admittance, can be thought of as the control law for the device. Goswami and Peshkin established a formulation to quantify the range of admittances passive devices could be designed to have.

One approach to building a programmably passive device is to develop programmably passive components. Laurin-Kovitz, et. al. have developed designs and prototypes of components with programmable stiffness and programmable damping[4]. The most recent work by Peshkin et. al. [5] explores the use of nonholonomic elements in implementing haptic displays. In this case nonholonomic elements are used to impose geometric constraints, as opposed to transmitting passive torques or forces. The idea is based upon using a nonholonomic element, such as a rolling wheel, as a continuously variable transmission (CVT), and then increasing its apparent degrees of freedom using feedback control.

3. Experimental Testbed

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 primary links labeled "1" and "2" in Fig. 1 have a coincident, stationary axis of rotation. The angular positions of these two links define the joint angles of the manipulator. The four electro-magnetic actuators, two brakes and two clutches, share a common axis of rotation with each other as well as with the driven links.

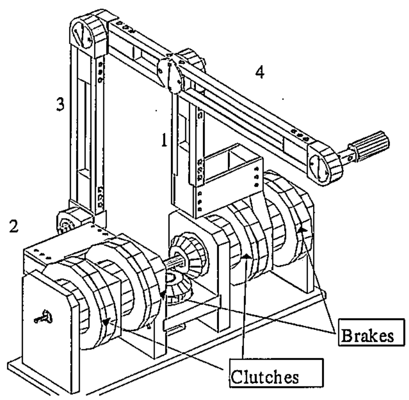

Fig. 1: The Passive Trajectory Enhancing Robot P-TER

The distinction between brakes and clutches lies in their function. Each driven link has a dedicated brake whose function is to remove energy from its corresponding link. The magnitude of the resistive torque transmitted by the brake is proportional to the applied current. The function of the clutch is to couple the two primary links together in some advantageous way. The control mechanism can be described as a superposition of the two separate devices 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.

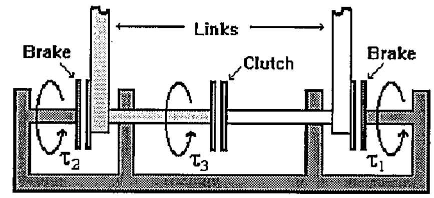

Fig.2: Direct joint coupling mechanism

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."

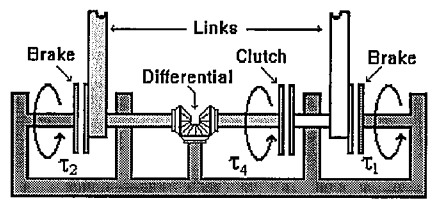

Fig. 3: Inverting joint coupling mechanism

The link lengths were chosen to eliminate all terms dependent on the cross-product of the two joint velocities in the equations of motion for the device. In addition, 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 (Fig. 4) gravity effects are eliminated.

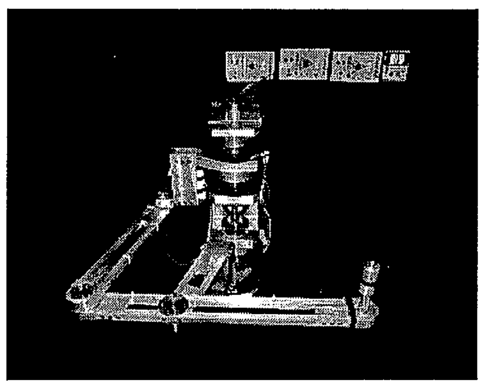

Fig. 4: P-TER: Current Configuration

P-TER 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 joint position signals are numerically differentiated to yield joint velocities. Digital low pass filters have been implemented to attenuate the noise added by the numerical differentiation, yielding a useful signal for the joint velocity.

4. Torque Translation Algorithm

In this section, an approach to selecting passive actuator excitations from general (active) control laws is suggested. The presented algorithm is a heuristic for choosing which passive actuators are to be used at which times to achieve the desired control torque as commanded by the controller. The formulation is based upon characterizing the capabilities of each of the actuators as a function of the manipulator joint velocities.

The action of each actuator, brake or clutch, depends upon the relative velocities of its friction surfaces. The relative velocity for a brake is simply the rotational velocity of its corresponding link. For the direct and inverting clutches, the relative velocities are the difference and the sum of the link rotational velocities, respectively. In the case of non-zero relative velocities, the *magnitude* of the transmitted torques is controlled varying the current to the device, thereby controlling the normal force between the two friction surfaces. The *direction* of the transmitted torque is such that it opposes the existing relative velocity. In the case of zero relative velocities, the magnitude can not be specified, and the transmitted torques can only act to resist any impending relative motion of the friction surfaces. Therefore, the torques which are transmittable are dependent upon the manipulator joint velocities.

The capabilities of the passive actuators are shown graphically as a function of joint velocities in Figure 5. The horizontal axis represents the angular velocity of joint 1, and the vertical axis that of joint 2. The joint velocity space is broken into octants by the 45 degree lines through the origin. Each of the octants is termed a *region*. The lines bounding each of these eight regions comprise eight additional regions. With the origin comprising a distinct region, this yields 17 regions in the joint velocity space. The regions are numbered counter-clockwise starting with the positive $\dot{\theta}_1$ axis.

Each region in the joint velocity space contains a corresponding set of labeled arrows. The arrows represent directions of torques that would be transmitted by exciting a particular brake or clutch in that particular state. For example, region 4 corresponds to $\dot{\theta}_2 > \dot{\theta}_1 > 0$. With the manipulator in this state, brake 1 will act to slow down link 1. Hence, the arrow for brake 1 is drawn to the left (negative $\dot{\theta}_1$ direction). Likewise, brake 2 acts to slow down link 2, and its corresponding arrow points downward in the negative $\dot{\theta}_2$ direction. Brakes 1 and 2 have only one corresponding arrow each, as their effect is always limited to one link only. The clutches, however, transmit torques of equal magnitude to both links. Therefore, two arrows are drawn to represent the actions of each clutch on both links. The direct coupling clutch tends to force the two links to rotate in the same direction with the same speed. In region 4, this will tend to reduce the speed of the faster link[1], link 2, and increase the speed of the slower link, link 1. This corresponds to one arrow to the right, and one arrow downward. Conversely, the inverting coupling clutch tends to force the links to rotate in *opposite* directions with the same speed. Since both links are originally traveling in the same direction, the slower link would have to change direction, and the faster link would slow down but maintain the same direction. This corresponds to negative torques on both links. Hence the arrows for the clutch are downward and to the left. Using this join velocity space, the capabilities of the passive actuators can now be visualized. The range of directions of the torque vector achievable by the actuators is limited to, at most, 135 degrees out of 360.

It is important to note here that Figure 5 is actually a superposition of two joint spaces. The primary axes shown define the *joint velocity space* which is divided into 17 *regions* as described above. Within each region, there is an additional set of vectors corresponding to joint torques. This sub-space is hereafter referred to as the *joint torque space*. Just as the joint velocity space is described in terms of regions, the joint torque space will be described in terms of *quadrants*.

The controller for P-TER specifies a desired torque with components in the joint 1 and joint 2 directions. The goal is to "assemble" this desired torque vector from the given possible actuator torque vectors.

The general approach followed by the algorithm is as follows. If the commanded torque is in the range achievable by the brakes alone, specify each component of torque independently with the corresponding brake. If the commanded torque is outside of the range achievable by the brakes alone, but within the range achievable by using a clutch, use the clutch along with one of the brakes to achieve the commanded torque. Finally, if the commanded torque is outside of the range achievable by either brakes or clutches, use one actuator only to achieve one of the two components of commanded torque.

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[1] The algorithm is described with the approximation that the link assembly inertias are roughly equivalent.

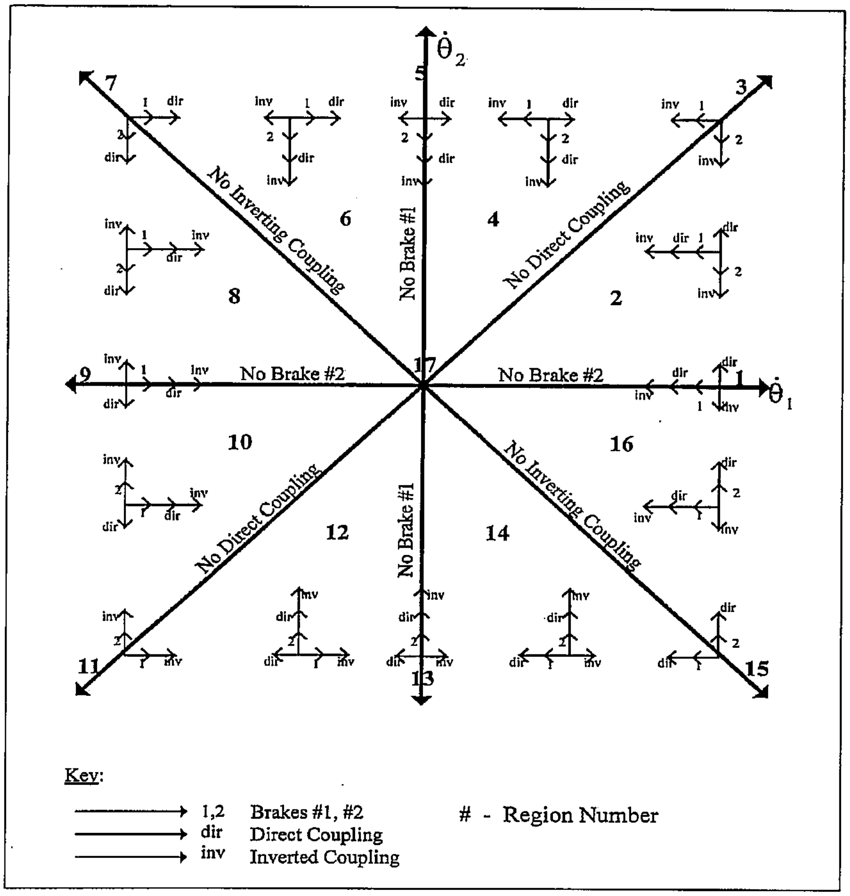

Figure 5 Torque Translator - Joint Velocity and Joint Torque Spaces

To illustrate the algorithm, attention is directed to Region 12 in the joint velocity space. It can be seen that, in general, the two brakes alone can be used together to provide any torque in **one** quadrant of the joint torque space, barring actuator saturation. In the specific case shown, it can be seen that the inverting coupling clutch provides no extra directional capability in assembling the desired torque vector. The direct coupling, however, expands the space of achievable directions to include one half of the adjacent quadrant. The control strategy for this case, region 12, is as follows:

1) Do not use the inverting clutch since it provides no additional directional capability.
2) If the desired torque is in the quadrant achievable by the two brakes, the 1st quadrant, then use the two brakes alone to provide the desired torque.
3) If the desired torque is in the upper half of the 2nd quadrant, use the direct coupling clutch to provide the horizontal, joint 1, component of the torque. Then use brake 2 to provide any additional desired torque in the vertical, joint 2, direction.
4) If the desired torque is in the lower half of the 2nd quadrant, use the direct coupling clutch only to provide the horizontal, joint 1, component of the torque.
5) If the desired torque is in the 3rd quadrant, use the direct coupling clutch only to provide the horizontal, joint 1, component of the torque.
6) If the desired torque is in the 4th quadrant, use brake 1 only to provide the horizontal, joint 1, component of the torque.

The case given above describes most of the regions of the joint velocity plane. Pseudo-code for the entire algorithm can be found in [3]. For the cases in which the use of one of the actuators is eliminated by its zero relative velocity, the range of achievable torques is reduced to a single quadrant. However, the rules for determining the remaining actuator excitations remain the same. In region 17, all joint velocities are zero, corresponding to the manipulator being, at least momentarily, at rest. In this case, none of the actuators are used.

Several observations of this case are noted. First, the desired torque can be provided *exactly* in the portion of the space defined by the brakes and the direct coupling clutch. If the desired torque is outside this space, then at least one of the components of the desired torque can be provided. Therefore, a passive actuator strategy can be determined in all cases. Secondly, at most two actuators need to be used together at any one time to achieve the resultant torque. This reduces the number of unknowns to two and the actuator torques can be solved for mathematically.

5. Experimental Results

The physical test bed has been interfaced to a PC with a 486 processor operating at 50 MHz for control. Code has been written to implement a standard impedance controller attempting to track a circle of constant radius in the presence of an arbitrary user input tip force. The impedance controller commands are filtered through the torque translation algorithm to generate passive actuator excitations. This controller is referred to as the *passive impedance controller.*

Preliminary experiments show the behavior of the manipulator in response to an actual human user input force signal. The user has reasonable knowledge of the desired path, and is attempting to traverse the entire circle. The results shown in Figure 5 show that it is indeed possible to implement a general control law with the torque translator on a passive device.

The vectors drawn at numerous points along the path indicate the magnitude and direction of the user input force at that point. The force vectors are plotted at 0.5 second intervals along the path. The manipulator follows a reasonably circular trajectory despite the arbitrary nature of the input force.

Several indirect measures of the performance of the torque translator were calculated. The 'percent achieved' statistic indicates the percentage of desired torque vectors which were located inside a region which was fully achievable by the torque translator. If the specified controller torque is not fully achievable, an approximated torque is commanded. It has been found that the percentage of fully achieved torque is consistently well under 50%. This is a direct manifestation of the passivity constraints. However, it is highly encouraging to note the prevailing utility of the device in spite of the constraints. The approximated commands provided by the torque translator still provide a high level of competence in completing the programmed task.

In the preliminary experimental trials, the clutches were used in the neighborhood of 50% of the time. This statistic gives an idea of how often the two brakes alone were inadequate in implementing the control torque and is a direct measure of the utility gained by adding the redundant actuators to the passive device.

6. Conclusions

The torque translation algorithm makes it possible to implement general control algorithms on a passive device by translating general controller commands into realizable actuator excitations. The algorithm uses manipulator state information with knowledge of the actuator capabilities to choose a favorable passive actuation strategy to implement the desired control law. The experimental results given here attest to both the performance of the torque translation algorithm, and to the level of utility attainable by passive mechanisms. The results given here are only preliminary, and do not suggest that P-TER is the best physical device with which to demonstrate performance. The bandwidth of the actuators is relatively low (approximately 8 Hz). The transmitted torque is based on a simplified friction model disregarding stiction, and is calibrated statically instead of dynamically.

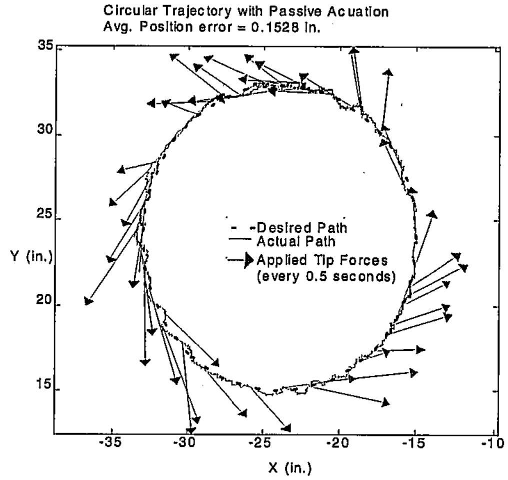

Figure 5 Experimental Trajectory tracking

7. Acknowledgments

This research has been partially supported by NSF Research Grant IRI-9526322.

8. References

[1] Book, W.J., R.A. Charles, H.T.Davis, M. Gomes, *The Concept and Implementation of a Passive Trajectory Enhancing Robot,* Proc. of the ASME International Mechanical Engineering Conference and Exhibition, 1996

[2] Davis, H.T., *An Investigation of Passive Actuation for Trajectory Control,* M.S. Thesis, Georgia Institute of Technology, School of Mechanical Engineering, Atlanta, GA, June 1996

[3] Goswami, A., and M.A. Peshkin. *Mechanical Computation for Passive Force Control,* Proc. IEEE Conf. on Robotics and Automation, 1993, pp. 476-483.

[4] Laurin-Kovitz, K.F., J.E. Colgate, and S.D.R. Carnes, *Design of Components for Programmable Passive Impedance*, Proc. of the 1991 IEEE Conference on Robotics and Automation, pp. 1476 - 1481.

[5] Peshkin, M., J. E. Colgate, C. Moore, *Passive robots and haptic displays based on nonholonomic elements*, Proc. of the IEEE International Conference on Robotics and Automation, April 1996, pp. 551 - 556.