Implementation of Arbitrary Path Constraints using Dissipative Passive Haptic Displays

A PhD Research Proposal Presented to the Academic Faculty by

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Abstract

The problem of applying an energetically passive dissipative haptic interface to a path-following application is addressed. This consists of controlling a man-machine system where the human operator provides all motive power, and the machine may dissipate or redirect this power. The goal of a controller is to constrain the operator-induced motion to a single arbitrary degree-of-freedom. This research will develop a generalized methodology for developing a path-following controller for any arbitrary dissipative haptic interface. A range of performance measurements will be developed to evaluate controllers. Controllers will be implemented on an existing two degree-of-freedom dissipative interface, and simulations will be performed for an interface with a higher number of degrees-of-freedom in order to validate the control methodology. Testing with human subjects will be performed in order to get real-world performance information; since the system inherently contains an operator, testing without human input is limited. The subject testing will also be used to generate statistically significant links between quantitative physical measured parameters and qualitative opinions of the users. This will assist designers by indicating what physical design parameters are critical to satisfactory operator opinion.

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1 Introduction - Energetically Passive Haptic Displays

This research will examine the ability of energetically passive haptic interfaces, specifically of the dissipative type, to simulate stiff constraint surfaces. These surfaces are used to guide the motion of the device to a specific point or area within the workspace, or to restrict motion to a certain region of the workspace. This type of display inherently has a human operator in the control loop, so evaluation of performance will require consideration of human behavior as well as analysis of the dynamics and control of the physical interface.

1.1 Haptic Interfaces

A haptic interface is a physical human-machine interface that interacts with a human user's sense of touch. Much as a video monitor and headphones provide information to a user through the sensor modalities of sight and sound, a haptic interface provides information through tactile and/or kinesthetic stimulation. Tactile stimulation can be thought of as "fine" touch— texture, temperature, vibration, etc.— and is usually presented to fingertips or the palm. Kinesthetic refers to forces and torques on and gross movement of joints and limbs.

The haptic interface is considered by many to be the next major step in human-machine interfaces (HMI). The visual and auditory modes are well established in practically every modern HMI, much research has been performed in these areas, and the current technology has matured to a point where it is in widespread use in the general population. Haptics is a relatively new field with a smaller research base, but in the past 5 to 10 years the amount of research being performed in the field has risen sharply. With more sophisticated interface hardware and control systems, innovative potential applications, and a better understanding of the psychology of tactile and kinesthetic perception, the technology of haptics is fast becoming a more commonly applied component of human-machine interfaces. This is illustrated by the recent success of several companies marketing haptics hardware and consulting services (e.g., SensAble Technologies, Immersion) and the marketing of consumer-level haptics hardware such as force-feedback joysticks and haptic mice.

1.2 Energetically Passive and Active Haptic Interfaces

Most research on and consumer application of haptic interfaces to date has been with energetically active interfaces. These are interfaces containing active actuators such as servomotors, hydraulics, or pneumatics which can provide motive power to the system. The flexibility and ease of control of such devices has fueled their popularity.

Some recent work, however, has been done in the field of energetically passive haptic devices. These are devices which may only store, redirect, and/or remove energy from the system. In other words, the actuators are not capable of moving the device on their own. Kinetic energy must be supplied from an outside source— the human operator— and the actuators work to dissipate or steer that energy.

While active devices are often more easily controlled— they are capable of generating arbitrary control forces which passive devices may not— a passive device has an inherent advantage in its safety. There are no active actuators to go unstable through electrical malfunction or failure of the control logic. In addition, there are well-documented problems with the human operator inducing instabilities in active devices. This is usually due to the fact that in designing the controller, the operator is normally considered to be a passive element— a condition that does not hold true in all situations. As new applications for haptic interfaces surface in areas where very large forces are involved (such as assisted manufacturing or whole-body interfaces) or when safety is absolutely critical (robot-assisted surgery or physical rehabilitation), the inherent safety of an energetically passive haptic interface becomes more attractive.

1.3 Classes of Passive Haptic Interfaces

There are currently two main classes of passive haptic interfaces that have been developed: dissipative and steerable. They differ in the nature of their actuators and of the manner in which control forces are developed. The dissipative type contains actuators which remove energy from the system. Dissipative actuators resist the motion of the device, often in a controlled manner.

Steerable interfaces work by constraining the workspace of the device to a number of degrees-of-freedom lower than the kinematic degrees-of-freedom of the device. The directions of the reduced degrees-of-freedom may be steered. The main example of this type of device is the Cobot, described in Section 1.4, which constrains the endpoint to a single steerable degree-of-freedom. Unlike a dissipative device, which works by resisting the user's motion, a steerable device theoretically has a negligible effect on the kinetic energy of the system.

There may, of course, be devices that are hybrids of the two main classes. Nominally, however, a device primarily belongs to one class while having secondary effects belonging to the other. One such device is PTER, which is presented later in this document and which will be used as a testbed for this research. PTER is primarily a dissipative device, but it may also be used in a reduced degree-of-freedom mode which is very limited compared to that of a true steerable haptic interface.

1.4 Existing Energetically Passive Haptic Devices

Several energetically passive haptic devices have been developed, though they are significantly outnumbered by active devices. This section presents several passive interfaces that have recently been developed.

A device developed in the Woodruff School and currently in use by the researcher is PTER, the Passive Trajectory Enhancing Robot [1]. This is a two degree-of-freedom device which uses four electromagnetic dry friction clutches to either variably couple the axes of the device or dissipate energy. Allowing the clutches to slip will dissipate energy from the system, and locking a clutch will restrict the motion of the device to a single degree-of-freedom. The direction of this degree-of-freedom is dictated by the kinematics of the device and is not steerable. Recent work with PTER has concentrated on improving dynamic response, smoothness of operation (or "feel"), and implementing feedback control of the actuators [2] [3] [4].

A team based at Northwestern University led by Colgate and Peshkin have claimed a new class of robots that they have labeled cobots (collaborative robots) [5]. These are nonholonomic haptic displays which use the concept of a continuously variable transmission (CVT) to couple the velocities of the generalized coordinates. These devices are kinematically single degree-of-freedom, but since this degree-of-freedom can be steered in task space, multiple degrees-of-freedom may be simulated with an appropriate control scheme. The cobot is the most straightforward example of a steerable passive haptic display.

PADyC (Passive Arm with Dynamic Constraints) has been developed under the supervision of Troccaz at IMAG-TIMC in Grenoble, France [6] [7]. It is an arm which uses two counter-rotating motors with custom overrunning clutches at each joint. These clutches allow the joint to move at any velocity up to the velocity of the motor to which it is attached. Two motors are used in order to independently constrain joint velocities in both directions. The motors do not supply power to the link, they only put an upper constraint on the magnitude of velocity. The human operator is free to move the device within the velocity constraints imposed by the motors and clutches.

Sakaguchi and Furusho at Osaka University have developed a two degree-of-freedom device kinematically similar to PTER, but which uses motorized electrorheological clutches [8]. These clutches use a fluid coupling which changes viscosity with applied electric field. By modulating the viscosity, the amount of torque transfered between plates of the clutch may be controlled. This device is active, but a passive ER clutch is currently under development in the Woodruff School with the intention of using it as an actuator in a haptic interface.

Will, Crane, and Adsit at the University of Florida have developed a six-degree-of-freedom hand manipulator that uses magnetic particle brakes as actuators [9]. Tajima, Fujie, and Kanade at Hitachi, Ltd., Japan, have built PALM-V^2, a mechanism that uses variable dampers to provide resistance to motion [10]. Both of these devices are dissipative.

2 Applications of Haptic Interfaces

2.1 The Three Primary Application Classes

There are three main classes into which applications of haptic interfaces may be divided. These are:

- Force-reflective masters for teleoperation
- Interfacing with virtual objects

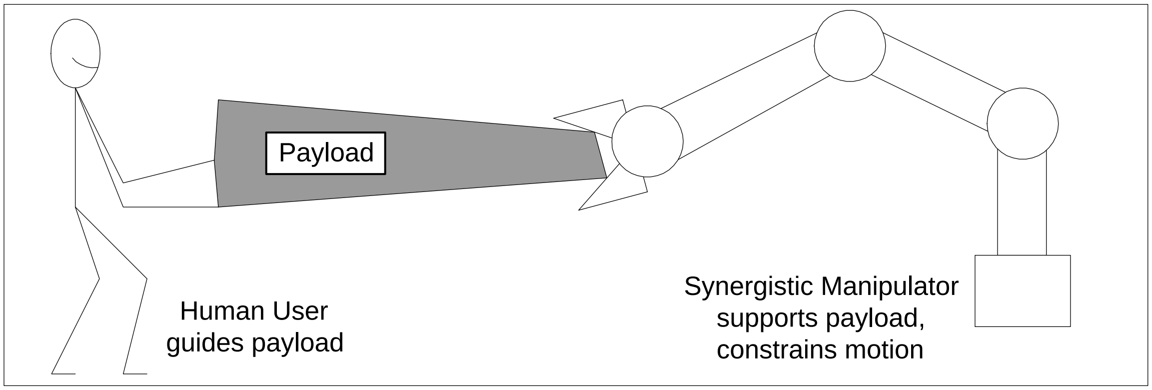

Figure 1. A Large-Scale Synergistic Device

- Synergistic devices

The first two classes, teleoperation and virtual environment simulation, are very similar in that they both involve interaction between the user/interface system and some intermediate medium. This medium translates the user's motion and the forces obtained from a slave robot (in the case of teleoperation) or a virtual environment simulation into commands to actuate the haptic device. The system as a whole is mechanically uncoupled. The only difference between the two classes is that in the case of teleoperation, feedback comes from a physical system and in the case of virtual environments, it comes from a model.

There are many real-life examples of the above applications. Force reflective teleoperation may be applied to practically any master used to control a remote device, be it a space-based manipulator, underwater service robot, search and rescue robot, or a bomb disposal robot. Force and dynamic modeling of virtual objects is useful in computer-assisted manufacturing for prototyping and assembly testing, physical rehabilitation, scientific visualization, and entertainment. There is a large body of research on both offline and real-time simulation of virtual objects and the calculation of rigid body dynamics, mechanical impedances, and contact forces.

In the applications described above, the user has direct interaction only with the interface, providing commands and receiving feedback that are filtered through a communication link and a control system. Troccaz, Peshkin, and Davies have introduced the term *synergistic* to describe devices which inherently involve coupled interaction between a tool or workpiece and both a human operator and a robotic manipulator [11]. See Figure 1. This is the third class of applications of the haptic interface, and is one that perhaps benefits most from the safety advantages of a passive interface.

An example cited by Troccaz, et. al. is an assist robot for cardiac puncturing. A surgeon manipulates an instrument, which is also attached to a robotic manipulator. The manipulator provides limited guidance of the instrument and consequently of the surgeon's hand. In this situation, the tool is mechanically coupled to both the human operator and the robot. This is in contrast to a teleoperated surgical setup, in which an independent and actively powered slave manipulator would hold the surgical instrument, and the surgeon would interact with it through control software by manipulating a master device, which could provide force feedback. In short, the added dynamics that exist between the user and the tool in a teleoperation system are not present in a synergistic device.

There are many advantages to synergistic devices over typical autonomous or teleoperated robotic manipulators in certain applications. The problem of realistic and stable force feedback from a teleoperated slave to a master robot is eliminated, as there is no intermediate medium between the operator and the tool or workpiece, so the operator feels the forces directly. Synergistic robots may make use of passive robotic elements, which improves safety in situations where the environment is delicate or when large forces are required. There have been several recent applications of synergistic devices to moving heavy payloads, amplifying human power, and assisted surgery, which are discussed in the next section.

2.2 Existing Applications of Synergistic Robots

Some applications for synergistic robots have been proposed or demonstrated. Schneider, et. al. have proposed a 6-DOF version of PADyC for use in the cardiac puncturing application mentioned above [12]. The skill of the surgeon at controlling pressure and needle penetration is important in this procedure. Schneider proposes the use of a PADyC device to guide and position the needle in the proper orientation, then constrain the motion of the needle to a single degree of freedom. The motion of the needle along this degree-of-freedom is then controlled by the surgeon. This allows precise, computer-controlled orientation of the surgical tool while retaining the skill and dexterity of the surgeon in performing the actual puncture. This example is one of a larger subset of potential applications in surgical tool guidance.

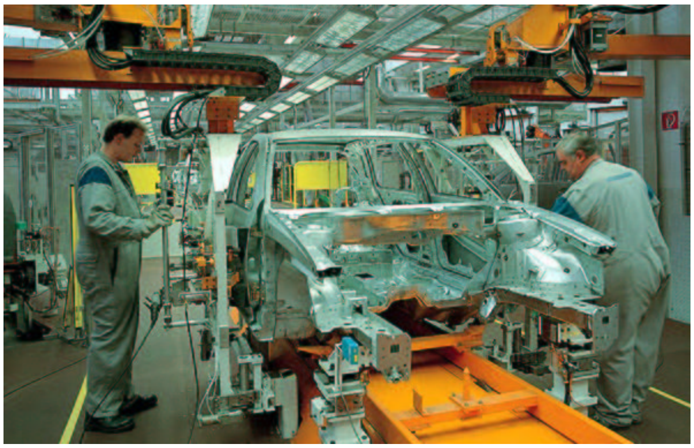

Figure 2. Line Workers using Active Assist Devices to Load Doors onto a Volkswagen Polo frame
(Photo courtesy VWVortex)

Most practical applications of cobots have come in the assisting of automobile final assembly. Currently active assist robots are being used in industry in applications such as door positioning and loading. Figure 2 shows workers using such assist devices at the Volkswagen plant in Wolfsburg, Germany, to load doors onto a prepared vehicle frame. Akella, et. al. describe the motivation behind and some examples of using passive cobots in this application [13]. Prototype cobots have been developed to assist in maneuvering dashboard assemblies and doors into and off of automobile frames. These devices allow a human operator to move the assemblies while the cobot provides directional guidance. When the particular assembly is near the target installation position, the operator may fine-tune the position according to differences in manufacturing tolerances and line positioning. This type of application can be extended to apply to many similar manufacturing tasks. There is evidence that providing external guidance to a human operator in a materials-handling task can reduce strain and fatigue on the operator [14].

The above two applications use passive devices. Other applications have been proposed for synergistic devices which utilize active elements. Several active synergistic surgical robots have been developed. These operate in similar modes a PADyC, but utilize powered actuators rather than dynamic constraints. One example of such a device is presented in [15]. While these actuated robots may prove more flexible in providing arbitrary forces, instability due to insufficient control laws or electrical malfunction could potentially put the patient at risk.

Snyder and Kazerooni propose a generic material handling system that is comprised of a powered exoskeleton which the human operator operates by applying forces to the device [16]. This device uses the concept of human amplification, which Kazerooni has developed with his concept of the human extender [17].

The U.S. Air Force has looked at an active synergistic device that would replace the existing munitions handler equipment that is used to load ordnance onto aircraft [18]. The existing hardware utilizes 1950's technology and is basically a truck with a hydraulic lift, which requires three operators. The proposed device is a human amplifier similar to a Kazerooni extender, which will allow the operator to more easily guide the ordnance into the proper position, and install it with help from programmed constraints.

Some work has also been done in the field of human-robot load sharing [19] [20] [21] [22] [23]. This involves an independent active robot manipulator which moves a payload which is also being manipulated by a human worker. The robot serves to support the weight of the object and perform inertia management while interpreting the loads exerted on the payload by the operator as guidance commands.

3 Passive Haptic Displays as Synergistic Devices

The array of existing and potential applications of synergistic devices make them an interesting topic of study. The safety aspects of passive haptic displays and the inherent physical coupling with the operator present in synergistic devices are complimentary. This section will discuss some of the general task requirements of synergistic devices, and compare the relative merits of dissipative and steerable interfaces when carrying out those tasks.

3.1 Tasks Required of Synergistic Devices

Synergistic devices are assist devices which act on a tool that is also being manipulated by a human operator. Despite the myriad applications of such a device, the functional requirements can be distilled to a list of basic tasks. These are free motion, weight support or gravity compensation, path following, obstacle avoidance, and haptic feedback effects. These tasks are explained below.

Free Motion: In this mode, the synergistic device allows free motion of the manipulator which is controlled by the human operator. In applications where the main purpose of the device is to prevent encroachment into a restricted area of the workspace or to register haptic effects in certain regions, the free motion mode is the default. Ideally, the system would have low inertia and negligible dynamic nonlinearities either due to physical construction or the action of an assist controller.

Weight Support or Gravity Compensation: In applications where the payload is heavy or bulky, the device could provide support for the weight of the payload, allowing the user to apply forces only for guidance or positioning. Using gravity compensation allows the user to position the payload vertically without having to fight gravity.

Path Following: This task involves constraining the motion of the payload to a reduced number of degrees-of-freedom. Normally, the operator is free to manipulate the device within the unrestricted degrees-of-freedom. The most basic example of this task is restricting the motion of an object along a line in space. Angular degrees-of-freedom may also be constrained in order to fix the orientation of the payload.

Path following may also be implemented as an inequality constraint. This would serve to present a virtual wall or surface. The path following task is carried out when the user attempts to move to one side of the path, but the system allows free motion on the other side.

Obstacle Avoidance: If obstacles are defined in the workspace, representing either real or virtual objects, the device may be configured to redirect the user around these obstacles as the payload is moved through the workspace. In absence of an obstacle, the device allows free motion in the workspace,

Obstacle avoidance could be implemented as a subset of path following; virtual walls could be placed around obstacles to redirect the motion of the payload. However, this is a conservative implementation. In general, the purpose of an obstacle avoidance system is to prevent penetration into obstacles and to redirect the user around them, not to constrain the device to a specific line or surface. There are methods that could be used to redirect the device without using stiff virtual walls. This is why obstacle avoidance is listed as a task separate from path following.

Haptic Feedback Effects: Although synergistic by nature of the direct coupling between itself, the payload, and the operator, the device is still a haptic interface. Conventional haptic effects may still be presented to the operator. Examples of these effects are force fields, vibrational feedback, and mechanical impedances.

3.2 Suitability of Steerable and Dissipative Interfaces as Synergistic Devices

Active and passive haptic interfaces differ in their ability to carry out the above tasks. In general, active devices are more flexible, but passive devices are still quite capable of acting as synergistic devices. In addition, the two types of energetically passive interfaces— steerable and dissipative— have contrasting capabilities when applied to the above tasks.

Free motion is possible with both active and passive interfaces. The construction of most active and dissipative passive interfaces allow free motion by simply shutting off the actuators. Backdrivable motors are present in virtually every active motor-driven interface to allow the user to maneuver the device. Steerable passive devices, however, must sense the user's intention and be controlled to allow arbitrary motion. Since only a subset of degrees-of-freedom are available at any point in time with a steerable device, the subset must be actively steered in order to align them with the direction in which the user wants the device to move. This may introduce problems in addition to the inertia and coupling present in active and dissipative passive interfaces. A steerable interface is limited in its illusion of free motion by actuator speed and force sensing ability (to determine user intent). A dissipative passive interface will perform better at allowing free motion, especially fine movements with low user forces and small displacements, than a steerable interface.

Gravity compensation is possible with active devices by adding a compensator to the control system, assuming that the actuators which move the payload vertically are sufficiently powerful to do so. Passive devices may not perform gravity compensation using actuator effort, however they may use static balancing to do so. This may be achieved with either counterweights or springs. Counterweights add extra inertia to a passive device, and designing a balancing spring network can be complex, especially for systems with large numbers of degrees-of-freedom. In the absence of gravity compensation, passive systems can at least be designed to support the weight of the payload. Conceivably, a braking system could be used to allow the user to lift or lower the payload to the required height and lock it in place once it is in position.

Path following or simulation of virtual walls is a common application of active interfaces. Typically an impedance controller is used, which simulates spring and damper elements between the payload and the desired path and applies forces to the payload equal to those exerted by these virtual elements. Although implementation of impedance controllers has been attempted on dissipative interfaces [24], the passive nature of the actuators limits the set of actuator forces at any given moment, and the forces required by the simulated impedance may not be achievable. A steerable passive interface, on the other hand, mechanically limits the motion of the endpoint to a subset of degrees-of-freedom. This makes path following a natural application of such a device. In the case of a kinematically one degree-of-freedom steerable interface, following an arbitrary path involves only steering the direction of that degree-of-freedom towards the desired path. For devices with more than one kinematic degree-of-freedom, however, it may be troublesome to constrain the motion of the device to fewer degrees-of-freedom.

Obstacle avoidance, as mentioned above, may be implemented by placing path constraints around the workspace. This method would be straightforward to implement with either an active device or a steerable passive device. However, as mentioned above, a dissipative passive device is not as nimble at simulating path constraints. However, there are other ways of implementing obstacle avoidance, such as the implementation of velocity fields around obstacles or simply immobilizing the device when near an obstacle. Some preliminary obstacle avoidance work has been done with PTER, illustrating that dissipative passive devices are capable of implementing obstacle avoidance with a satisfactory level of performance and haptic quality [25]. This work is discussed further in Section 5.1.

Haptic feedback effects are not required by all synergistic applications, but may be required by some, or may be determined to improve the performance of certain tasks. These effects comprise simulation of compliances or admittances, presentation of vibrational or periodic effects, or generation of force fields. These tasks are best provided by active devices, as they mostly require the application of arbitrary forces to the user. Dissipative passive devices are capable of exerting forces on the user, but forces are limited by the passivity of the actuators. Steerable devices are not designed to deliver forces at all, and perform poorly at providing these effects.

3.3 Emulating Stiff Surface Constraints with Dissipative Passive Haptic Interfaces

From the discussion in the previous section, one may conclude that for many applications, passive haptic interfaces are suitable for use as synergistic devices. When compared to active devices, passive interfaces are not as adept at providing gravity compensation or certain haptic effects, but they may perform the other tasks at a satisfactory level. In addition, passive devices have the advantage of increased safety over their active counterparts, which is all the more critical in delicate environments or with heavy payloads.

Dissipative devices are inherently better at allowing free motion of the payload, while steerable devices are more suited to providing path constraints. The two types of devices exhibit similar performance in carrying out the other tasks mentioned in the previous section.

Comparisons can also be made between dissipative and steerable interfaces on a non task-specific basis. Dissipative devices are typically less complex than steerable devices, especially for workspaces with a high number of degrees-of-freedom. Cobots built by the team at Northwestern use custom continuously variable transmissions [26], which are difficult to construct and are limited in the maximum steering forces that they can exert. Dissipative devices may use off-the-shelf components such as electromagnetic clutches or magnetic particle brakes. Also, steerable devices must have additional dissipative or locking elements in order to have the ability to totally immobilize the payload. Some dissipative devices (such as PTER) may use their main actuators to immobilize the payload without the need for additional hardware.

From the above discussion a claim can be made that dissipative passive haptic interfaces are equally or more capable than steerable interfaces at serving as synergistic devices except in providing path constraints. Can a dissipative device be controlled to provide path constraints equally as well as a steerable device? If not, does the difference compared to steerable passive or active haptic devices significantly effect the performance of the device or the opinion of the human operator? Which type of device does the operator prefer to use? These questions illustrate the basis of this research, which is proposed in the following section.

4 Proposed Research

4.1 Implementing Path Constraints with Dissipative Passive Haptic Interfaces

Since the biggest weakness of dissipative passive haptic displays used in a synergistic application is their ability to implement path following, it would be interesting to formally investigate their true capabilities in carrying out this task.

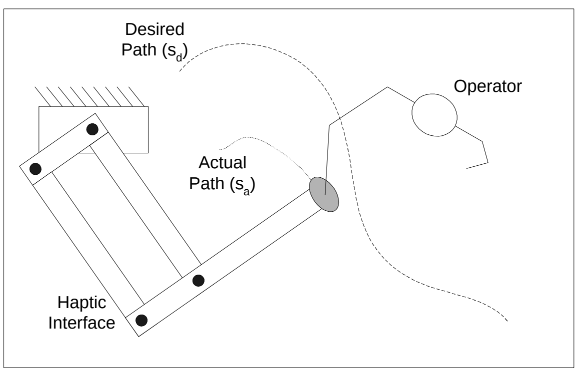

Figure 3. Operation of a Path Following Controller

The first step of this research will be to develop one or more control systems that may be used to perform path following on dissipative passive haptic displays. See Figure 3. A path following controller must guide the motion of the device towards and along a desired path s_d.

Parallel with the control system(s), general methodologies will be developed to apply them to any dissipative device.

Currently the envisioned controller is velocity based, building on the work documented in [24] and [25]. Such a controller attempts to redirect the velocity vector of the device towards a desired direction. Desired velocities are position dependent, defined as a velocity field in the workspace. Previous work focused on computing forces based on velocity errors. Given the inherent limitation of passive devices in generation of arbitrary forces, the desired forces computed by the controller may not be achievable. The controller developed in this research will focus on modulating the velocities of each axis of the dissipative device.

Li and Horowitz have developed a passivity-based velocity controller which has been used to implement contour following on active robotic hardware [27] [28]. This controller is based on passivity theory to ensure the safety of the device when interaction with the environment is necessary. Their controller simulates a nonlinear damper element which acts on the velocity error. They also add an imaginary degree-of-freedom to the device in order to store energy. This extra modeled degree-of-freedom acts as a simulated flywheel, able to take energy out of the device and reapply it at a later time. Since it is an energy storage element with zero initial conditions, the overall system remains passive.

Although initially designed to work with an active device, Li and Horowitz illustrate how their controller may be implemented on a one degree-of-freedom device by using passive elements, specifically tunable dampers and a spring [29].

There are major differences between the controller proposed by Li and Horowitz and the velocity controller that will be developed in this research. First of all, their controller depends on having an energy storage element. In general, dissipative devices do not have any such elements. Second of all, although they touch on implementing their controller with passive elements, this is not the same as starting with a device with defined construction and existing actuators and developing a controller for it. The methodology developed in this research will work for all dissipative devices in general, without requiring hardware modification of the device. Lastly, the example given in [29] is for a one degree-of-freedom device, and requires 4 tunable dampers and one spring element. Expanding this to a multiple degree-of-freedom device will result in a large number of required actuators, and will introduce a high amount of design complexity.

A general velocity control methodology for a dissipative passive haptic interface should apply to devices of any degree-of-freedom, with and without coupling elements. For example, PTER has two purely dissipative actuators and two coupling actuators which may be used to transfer kinetic energy between the axes of the device. A general methodology should include these coupling elements, but also work with a device using only dissipative actuators.

In addition to the development of a velocity-based path following controller, the single degree-of-freedom (SDOF) controller used in [25] may be investigated. This controller has some benefits over the velocity based controller, namely its simplicity, but it may only be implemented on devices which have the ability to lock their actuators with a high level of resisting force. PTER is one such device with this capability. Adding a second locking actuator to each axis of non-lockable devices is a possibility, but this is not an ideal solution.

The SDOF controller was developed to implement obstacle avoidance, but it could be reworked in order to apply it to path following. This would be done by creating a virtual corridor around the defined contour to be followed out of SDOF lines. In its current incarnation, the constraint lines used by the SDOF controller must be defined by hand. A more automated procedure for defining the lines based on desired trajectories will be considered. Also, the SDOF controller was developed specifically to be used with PTER. A more general controller which may be applied to any lockable interface will be developed.

Matsuoka has implemented a similar controller on a three DOF dissipative device [30]. Rather than constraining the device to a single DOF, her controller restricts the device to two DOF. The controller was implemented in a virtual reality application, used to simulate contact with virtual objects.

Controllers will be evaluated using both simulation and experimental data. The experimental setup that will be used to perform experiments is discussed in the next section, followed by a discussion of evaluating controller performance. The experimental setup will be based on PTER, which is a two degree-of-freedom device. Simulations will be used to verify operation of the controllers before experimental implementation, and to show the validity of using the methodologies on devices with a higher number of degrees-of-freedom.

Initial work on controller development is discussed in Section 5.2.

4.2 Experimental Testbed (PTER)

In order to obtain experimental data on the performance of path following controllers, PTER will be used as a testbed. The general methodologies developed for designing the velocity-based and SDOF controllers will be applied to PTER's configuration. PTER is an ideal testbed, as it is fully dissipative and has coupling elements. The controllers can be designed both with and without inclusion of the coupling elements. Performance of the pure dissipative and dissipative-plus-coupling setups can be compared in order to study the benefits of including coupling elements in the design of the interface.

When applying the controllers to PTER some aspects of the physical system must be accounted for. PTER is equipped with digital encoders to measure the position of each link. The link velocities must be estimated from the position measurements. The velocity controller depends heavily on this estimation. Estimating velocity from discrete position measurements is a well-established problem, and one without any definitive solutions. Presently, a 4th-order Butterworth filter is used in PTER's control code to filter out high-frequency noise caused by numerical differentiation. This method has yielded some success, but other alternatives will be investigated.

PTER also has some complexities in its actuator dynamics. The clutches for the most part act as first-order systems relating clamping force to commanded amplifier input. When moving, a clutch generates torque roughly proportional to the clamping force, but when locked the clutch is in a static friction state, and the generated torque depends on applied torque. Transitions between static and dynamic friction introduce nonlinear friction effects such as stiction and stick-slip. These are difficult to model, and the behavior of the clutches in transitionary states is thusly hard to predict. There are also air gaps between the clutch plates when the clutch is unactuated. This introduces both a time delay and a sharp torque spike when the clutches are first activated. The time delay is caused by the need for the plates to close the gap and make contact, and the torque spike is caused by the high momentary reaction forces caused by the inertia of the clutch plates.

All of the above actuator dynamics must be taken into account when designing a controller for PTER. Further information about these issues is presented in Section 5.3.

4.3 Measuring Performance and Human Subject Testing

When performing both simulations and experimental testing, a method of measuring performance of the developed controllers is necessary. Given the inherent inclusion of the human operator in the control loop, there are both quantitative and qualitative measurements that are relevant. Quantitative measurements such as total path-following error will be measured in both simulation and experiments. Qualitative measurements will be taken through the use of surveys in the human subject testing. This is not possible in simulation, of course.

Human subject testing, and the development of good survey questions and their appropriate analysis is a time-consuming process. It is, however, necessary in order to evaluate a human user's satisfaction with a given device and controller. It would be ideal to be able to correlate certain quantitative physical measurements with corresponding qualitative user opinions. If this was possible, then a designer of a path-following device and/or controller would be able to optimize certain quantitative performance measures, confident in the fact that the operator will be satisfied with the operation of the device. This research proposes to develop such a correlation.

There will be two types of tests performed: basic and task-based. The basic tests will study some of the fundamental issues in presenting path constraints with a dissipative passive device. The task-based tests will evaluate the performance of the operator executing simulated real-life tasks, such as a peg-in-hole task.

When implementing a path constraint, the user should be able to freely move the payload along the direction of the path (perhaps against some viscous resistance), while applying arbitrarily large forces perpendicular to the path. This situation results from locking one of PTER's clutches and allowing the user to move along the resulting single-DOF line, as long as the user's perpendicular applied force does not overpower the maximum static torque achievable by the locked clutch. The performance of a path-following controller depends on how well it simulates these conditions along any arbitrary direction.

When moving along a hard contour, energy is conserved other than any that is lost through sliding friction tangent to the contour. When simulating this condition with a dissipative device, forces come through dissipating energy, except in certain cases when a device is lockable and the desired path aligns with one of the locked axes. What are the implications of using a dissipative device to simulate an essentially non-dissipative physical phenomenon? It is proposed that the allowance of forces in directions perpendicular to the desired path without accompanying motion will result in favorable user opinions of the controller operation.

The basic tests will consist of first allowing the user to move PTER along a SDOF line and measuring the user applied forces tangent and perpendicular to the SDOF line. Then, the user will move PTER along an arbitrary path under control of the path-following controller, again measuring applied forces. Users will be presented with questions about how the controller compares to the SDOF case. In order to facilitate analysis, most of these questions will be direct comparisons or yes/no type questions.

In addition to the basic tests, task-based tests will be performed. The standard peg-and-hole task will be used as the basis for these tests. This task involves guiding the user from a starting point to a target point with minimum forcing in a minimal amount of time.

In order to measure performance during the above tests, physical parameters must be defined which have a direct relationship to the performance of the device. Typical parameters used to evaluate controllers may not apply in this situation, as the controller does not fit into the typical controller framework. The actuators are limited in the sign of their effort by the passivity constraint. The majority of outside disturbance in the present system comes from the action of the human operator, who is the source of all motive power, and who is also very difficult to model. These factors lead to a search for customized measures of controller performance.

The controller seeks to guide the path of the device s_a to follow a desired path s_d (see Figure 3.) The desired path is arbitrary, and may contain up to six DOF. To eventually align with the desired path, the magnitude of the path error $|\bar{x}_e|$ should approach zero

$$\lim_{t\to\infty} |\bar{x}_e(t)| = \lim_{t\to\infty} |(\bar{x}(t) - \bar{x}_d(t)| = 0 \quad (1)$$

where $\bar{x}(t)$ is the position of the device at time t and $\bar{x}_d(t)$ is the desired position at time t. The desired position is the point on the path nearest to the actual position of the device. Bold variables represent vectors of dimension appropriate to the workspace.

Given the objective in Equation 1, cumulative path error $e_c(t)$ would be the first and most logical measure of performance.

$$e_c(T) = \int_0^T |\bar{x}(t) - \bar{x}_d(t)| \; dt \tag{2}$$

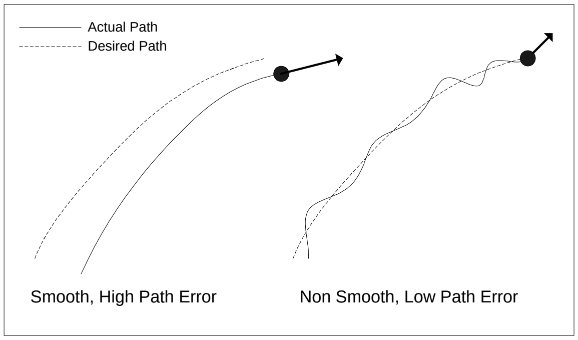

Figure 4. Smooth and non-Smooth Execution of Path Following

In addition to approaching the desired path, smooth movement of the device is desired. This is desired to maximize speed of travel along the path, and to improve the feel of the device to the operator. In some cases, a high level of smoothness is desired over a low cumulative path error. For the two cases shown in Figure 4, the controller yielding higher path error but smoother operation may be preferable.

Smoothness can be elusive to measure quantitatively. Two possible measurements are proposed. The first is simply the derivative of the path error. If the path error derivative is high, the error is changing quickly, which would indicate a high velocity perpendicular to the desired path. Below is an expression for the cumulative path error derivative.

$$e_c(T) = \int_0^T \left(\frac{d}{dt} |\bar{x}(t) - \bar{x}_d(t)| \right) \; dt \tag{3}$$

The second measure of smoothness is the number of crossings of the desired path per unit length of that path.

$$n_l(t) = \frac{n_c(t)}{|\bar{s}_d(t)|} \tag{4}$$

where $n_c(t)$ is the total number of path crossings at time t and $\bar{s}_d(t)$ is the total desired path length traveled at time t. A low value of $n_l(t)$ is desirable. In order to implement this measure in an actual control system, an efficient method of detecting path crossings for up to 6 DOF is necessary.

In addition to the primary performance of the path following task, there are secondary effects of the controller which may have an effect on the operation of the system as a whole. Since the human operator is an integral link in the system, it is paramount that the device not cause undue stress or fatigue on the user. This is especially important when a synergistic device is deployed in a commercial or industrial environment, and a user may be working directly with the device for many hours of the day. Two measures of this are the magnitudes of the average force F_a exerted by the device and average jerk J_a, which may be responsible for vibrational fatigue.

$$F_a = \frac{1}{T} \int_0^T \bar{w}_f |\bar{F}(t)| dt \tag{5}$$

$$J_a = \frac{1}{T} \int_0^T \bar{w}_j |\bar{J}(t)| dt \tag{6}$$

$\bar{w}_f$ and $\bar{w}_j$ are weighting vectors. $\bar{F}(t)$ and $\bar{J}(t)$ are the forces and jerks, respectively, exerted by the actuators at time t.

For the task-based tests, i.e. the peg-in-hole test, the time to completion will be used as another measure. This does not directly measure the path following performance, but is an important factor if the device is applied to a practical application. A controller which follows the path very closely yet severely resists the

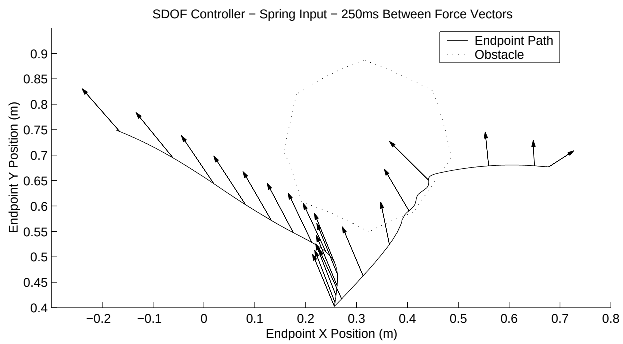

Figure 5. Obstacle Avoidance with PTER:
SDOF Controller, Spring Input

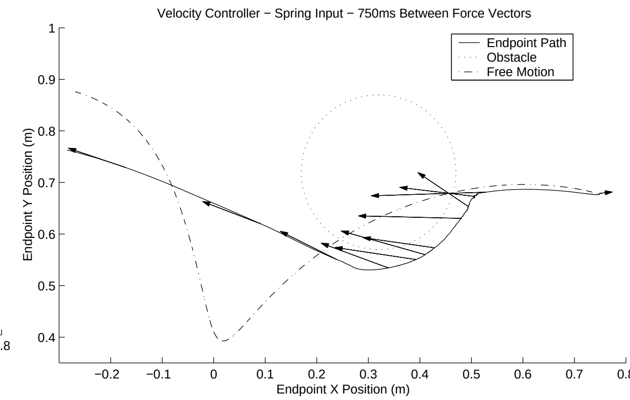

Figure 6. Obstacle Avoidance with PTER:
Velocity Controller, Spring Input

user's motion may not be as desirable as a slightly less accurate controller which allows the user to quickly complete a task.

All of the above measurements are important in evaluating performance, but a method of combining them into one or more summary measurements must be devised. This process will depend partially on human subject testing, and may not be able to be fully settled until testing is done and all of the data has been acquired. This is due to the fact that it is presently unknown how much weight should be placed on each of the above measurements. A statistical analysis, likely using standard ANOVA methods, will be used to look for correlations in the measured data and the user's opinion of the operation of the controllers. A sufficient number of test subjects will be required in order to make the results statistically significant. Presently at least 10 to 15 subjects are envisioned. Any correlations may be used to determine what physical parameters are important to the user. Combining user opinion with the physical requirements of the task at hand will allow development of one or more global measures of performance.

5 Initial Work

5.1 Obstacle Avoidance using PTER

Some initial work has been done using PTER for obstacle avoidance [25].

Two controllers were considered— a velocity controller originally described by Gomes [31] and a new "single degree-of-freedom" controller. The velocity controller attempts to control the velocity of PTER's endpoint. The desired velocity is obtained from a velocity field defined around obstacles which attempts to drive the tip in a direction parallel to the surface of the obstacle. It also completely immobilizes the tip if it penetrates an obstacle. The forces requested by the controller are not always available due to the passivity of PTER. The controller attempts to achieve a commanded force as close to the desired direction as possible, but in cases of extreme uncontrollability, it completely immobilizes the device. Any controller-induced immobilization is released if the controller detects the user pushing away from the obstacle.

The single degree-of-freedom controller, or SDOF controller, controls the tip by selectively locking up one of PTER's clutches which reduces the number of kinematic degrees of freedom from two to one. This controller provides very smooth operation, but does not provide for arbitrary obstacle shapes. Any obstacle must be comprised of lines representing the single degrees of freedom available from locking a clutch at a given position.

Figures 5 and 6 show test results using the velocity and SDOF controllers. These tests were performed by starting PTER in a predefined configuration, attaching a constant-force spring to PTER's tip, and releasing it. Although this test does not involve human power or interaction, it is very repeatable. A repeatable test with well-defined conditions was deemed appropriate to compare the velocity and SDOF controllers. In both plots, the solid line shows the position of PTER's tip as it moves from right to left. The arrows represent the force vectors applied by the spring onto the force sensor mounted to PTER's handle.

It can be seen from Figures 5 and 6 that both controllers redirect the tip of PTER around the obstacle. In Figure 6, the dash-dot line is the motion of the tip when the controller is not on. It is clear that the tip would pass through the obstacle if it weren't for the influence of the controller.

More detailed information on these tests may be found in [25].

5.2 Initial Work on Implementation of Path Constraints

The experience with the controllers described in the previous section will be used to implement path following controllers.

Some initial work has been done on developing a methodology to design a velocity-based path following controller for any arbitrary dissipative device with up to 6 controllable degrees-of-freedom.

Given a desired path through the workspace s_d, a velocity field must be defined in accordance with that path. The field, if enforced by the controller, should guide the device towards the path and along the path from any starting point in the workspace, regardless of user input. For the initial development, it is assumed that the user is attempting to follow the path under guidance by the controller. Additional logic will be necessary later on to allow for user inputs which do not result in an achievable motion back towards the path. This will likely result in the immobilization of the device, if possible, or at least very high resistive forces; if the controller can not guide the user back to the path, the best it can do is to prevent the user from straying even further. If a force sensor is present, it may be used to sense when the user is applying force once again in the desired direction of motion, and the device may be freed.

The velocity field $\bar{V}_f(\bar{x}, \dot{\bar{x}})$ defines at least one velocity direction for each position in the workspace. Depending on the current direction of motion of the device, there may be different desired velocities at the same point in the workspace. This will assure that the controller will operate regardless of the direction of motion along the desired path.

It is important at this point to make the distinction that the velocity field provides a desired direction of motion. The magnitude is unimportant— it should be controlled by the user. Additional features may be added to the control system to provide viscous resistance or perhaps an upper limit on velocity, but inherently the velocity field only provides a desired direction. All vectors contained in the velocity field may be unit vectors.

Once a desired velocity in the cartesian workspace of the device has been defined, that velocity may be transformed into joint-space, resulting in desired velocities of each of the coordinates of the device. Assuming that the system has an invertible Jacobian:

$$\dot{\bar{\theta}}_d = \mathbf{J}^{-1}\bar{v}_d \tag{7}$$

Define a coefficient vector $\bar{c}$ such that

$$\dot{\theta}_{di} = c_i\dot{\theta}_{ai} \quad \text{for} \quad i = 1 \rightarrow m \tag{8}$$

where m is the number of DOF, $\dot{\theta}_{ai}$ is the actual velocity of link i, and $\dot{\theta}_{di}$ is the desired velocity of link i, computed from Equation 7. This coefficient vector defines the ratio between the actual velocities and the desired velocities, and may be used as a basis for control.

$\bar{c}$ is normalized by dividing it by its largest positive component:

$$\bar{c}_n = \frac{\bar{c}}{c_{max}} \tag{9}$$

This allows the minimization of energy removed from the system. Assuming the uncoupled case, where the system has only dissipative and no coupling elements, no axes may be sped up, so all axes except for the axis with 1 in $\bar{c}_n$ must be slowed down. For each of the individual axes, if $c_{ni} > 0$, braking force should be applied. If $c_{ni} = 0$, the axis should be immobilized. If $c_{ni} < 0$, however, the desired velocity is of opposite sign of the actual velocity. Sign changes are impossible to achieve in an uncoupled system through actuator effort, so the best that the controller can do is immobilize the axis. If c_{ni} is negative and very large, that could signal a high degree of deviation from the desired velocity, and it may be desirable to immobilize the entire device until the user attempts to steer the device back towards the desired path.

If all members of $\bar{c}_n$ are close to 1, that means that the actual velocity is very closely oriented with the desired velocity. Since the above framework does not actuate the velocity with the coefficient of 1 in $\bar{c}_n$, it is conceivable that in the above case, the unactuated axis could be rapidly changing with very small changes in velocity direction. This may lead to chatter, or an excessive on-off motion of the actuators, which can be fatiguing to the user. One solution to this would to turn off the controller completely when all coefficients of $\bar{c}_n$ are within a certain range close to 1. Another solution would be to filter the control inputs to the actuators in the same situation.

Once $\bar{c}_n$ is computed, it may be used to generate the system inputs, $\bar{u}$. A simple linear control law would be:

$$\bar{u} = g(\bar{1} - \bar{c}_n) \quad \text{where} \quad \bar{1} = \left\{ \begin{array}{c} 1 \\ \vdots \\ 1 \end{array} \right\} \tag{10}$$

g is a gain constant, and may be set to the limit of the actuator effort. This would result in a controller with a linear effect from zero actuation when c_{ni} is 1, to full effect when it is zero. The controller would saturate at negative values of c_{ni}. Another possibility would be a quadratic or exponential relationship, which would reduce the effect of the controller when near the desired velocity. Simulations will be used to evaluate several different control laws based on $\bar{c}_n$.

The above analysis is for a device with no coupling actuators. When such actuators are used, there is potential for much more flexibility in control. The main contribution of coupling actuators is the ability to transfer energy between the system axes, whereas without them energy may only be dissipated. Transferring energy rather than dissipating it has the potential for reducing fatigue of the user. Matsuoka has shown that a device that is kinematically non-orthogonal may not be capable of producing forces directly opposite to the direction of motion in all cases [30]. This limitation could hamper the implementation of satisfactory viscous fields if such an effect was desired. It is thought that the addition of coupling actuators may provide for this ability in non-orthogonal devices. A complete analysis will be carried out in the course of the research.

The development of a controller for an device with coupling actuators can become complex. Such a controller must support an arbitrary number of actuators coupling different axes. This can result in a high number of actuators to control for a device with high DOF. A 4 DOF device with all axes coupled will have a total of 10 actuators to control. The above control concept will be expanded in the course of the research to include coupled actuators. It may be possible to develop a single control methodology that will work for devices both with and without coupling actuators if purely dissipative actuators are modeled as coupling actuators which couple their axis to ground.

Another issue to be dealt with is behavior of the controller at low velocities. The case of having the actual velocity be very close to the desired velocity was discussed above. This could result in a high frequency of actuation as the dominant direction changes. A similar condition could be caused at low velocities, where very small motions and force inputs can have a great effect on the direction of the actual velocity of the device. A possible way to deal with the low velocity case is to rely more on the input from the force sensor. The operation of the actuators may be controlled according to whether or not the user is attempting to guide the device towards the desired path.

A preliminary version of the velocity controller was implemented in an existing simulation of PTER. The desired path was a straight line through the workspace at $y = 0.6$ m. The device starts on the path and a constant external force tangent to the path is applied to the device, as well as a perpendicular disturbance force consisting of a sum of several sinusoids. The controller uses the control law of Equation 10, modified by a term which decreases the effect of the controller when path errors are low.

$$\bar{u} = g(\bar{1} - \bar{c}_n)\frac{|\bar{x}_e|}{0.001} \tag{11}$$

When an actual link velocity is zero, the coefficient c_i for that axis is undefined. In this case, the controller looks at the component of the user's input force acting on the axis. If it is pushing away from the desired direction of motion, a full-scale command is sent to the actuator. If the user is pushing towards the direction of motion, no actuation is commanded, and the axis is allowed to start moving in the desired direction.

Figure 7 shows the results of the simulation. Although the motion of the tip appears jerky, the controller keeps the motion constrained close to the desired line. The maximum path error was 16 mm and the average

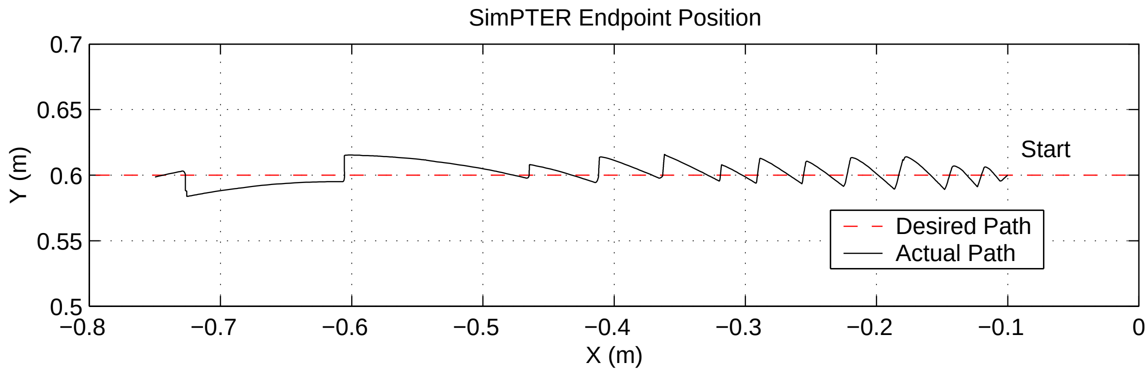

Figure 7. Simulation Results of Velocity-Based Line Following Controller

error along the path was 6 mm. Total distance traveled along the path was 650 mm. The encoders are not modeled in this simulation, but the friction interface and time delays introduced by the actuators are. The issue of velocity estimation will be addressed when a controller is implemented on PTER, as will a more optimum control law and any ancillary control logic. This simulation, however, serves as a proof of concept that the velocity-based path constraint controller will work.

5.3 Using PTER as a Testbed

There are several nonideal physical properties of PTER which must be taken into account when implementing any control system. PTER uses digital encoders to measure the position of each link. These have a very high resolution (16000 counts per revolution). While this allows a very accurate measure of the position of PTER, calculating velocity from position encoders is a well-established problem, and one which has not been definitively solved.

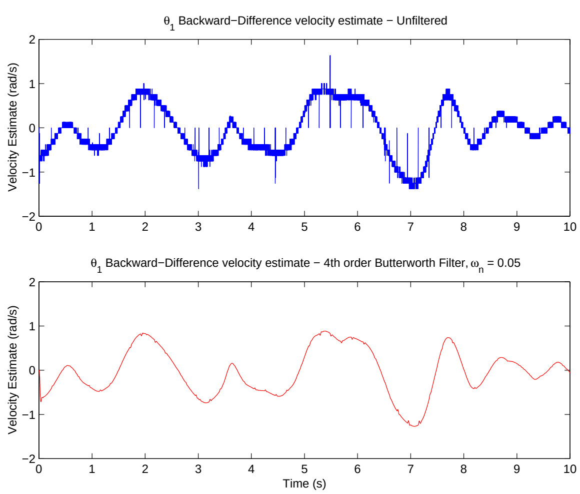

Figure 8. Differentiation-induced Noise in Estimating PTER Joint Velocity

Using a straight backward-difference calculation to estimate velocity from sampled discrete position measurements introduces a high amount of numerical differentiation noise. This can be seen in the upper plot of Figure 8. One joint of PTER was moved back and forth, and the position of the link was measured. Figure 8 shows the backward-difference velocity estimate, computed as

$$\dot{\theta}(kT) = \frac{\theta(kT) - \theta((k-1)T)}{T} \tag{12}$$

The estimated velocity has low resolution, which gets worse with lower sample period. If velocity is going to be used as an input to a velocity controller, the straight backward-difference is not a satisfactory way of estimating velocity due to it's low resolution and high amount of fluctuation, especially when at low velocities. The zero-velocity spikes are believed to be an artifact of the acquisition hardware, and will be fully addressed when controllers are implemented.

A filter is currently used with some success to smooth out the estimated velocity signal. The filtered data is shown on the lower plot in Figure 8. A 4th-order Butterworth filter is implemented in software with a cutoff frequency of 100 Hz. The sample period of the controller is 1 kHz. The filtered estimate is definitely smoother than the original estimated signal, which is very important if it is to be used as an input to a velocity controller. However, the inherent resolution of the original signal is still low, and the filter introduces some phase lag into the estimated velocity.

In order to improve resolution, especially at low speeds, the method of Janabi-Sharifi, Hayward, and Chen will be implemented [32]. This method effectively uses an adaptive sample time to compute the backward-difference. At high velocities, the sample time is low in order to quicken the response time of the filter, while at low velocities the sample time is lengthened in order to increase the resolution of the estimate.

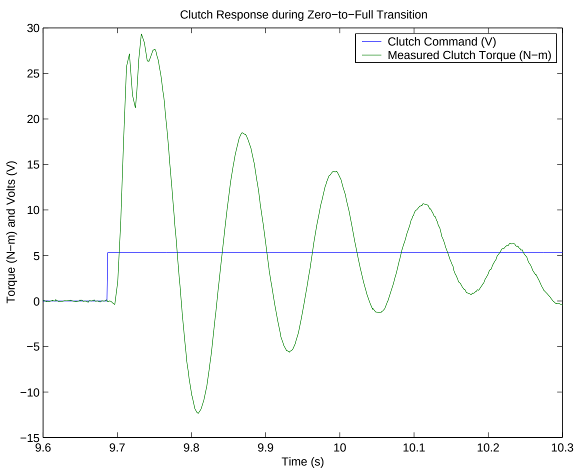

Figure 9. Step Response of PTER's Clutch 3

Another mechanical issue lies in the clutches themselves. Figure 9 shows the command and measured torque from clutch 3 when the device is moving freely and the clutch is suddenly applied. There are two main effects to be noted: a slight time delay, and the high amount of oscillation. The time delay is introduced by the air gap between plates of the clutch. When the clutch is applied from zero, it takes a finite amount of time (about 0.02s) for the plate to bridge the gap and start creating torque. By realigning the clutches, this gap should be able to be reduced.

The other effect is the severe oscillation. In the plot, the initial torque peak slows down the clutch. During the short period of sustained torque at the top of this peak, the clutch plates are brought to rest. After this period, when the high-amplitude oscillations occur, the clutch is in a static friction mode, and is effectively locked. The oscillation is caused by compliance in the clutch spokes used to measure generated clutch torque. It is not yet known if this oscillation is detrimental to the operation of the device. It seems as though in some situations it may actually be beneficial, providing a base level of stiffness unable to be modeled through actuation of the clutches when emulating surfaces. If the oscillations do prove troublesome, the spokes may be replaced with non-instrumented solid ones. These do not have torque-sensing capability, but will yield a much higher compliance of the locked clutches, and will result in a lower amplitude of oscillations.

A control system has already been implemented on PTER using QNX for a real-time operating system and a commercial Servo-to-Go interface card. The software is very modular, and new controllers may be easily added and modified.

6 Conclusion

6.1 Goals and Contributions of this Research

In summary, the purpose of this research is to investigate the use of dissipative passive haptic interfaces to present path constraints to a human operator. This will involve controller development, testing, methods of performance evaluation, simulation, and human subject testing.

The goal is to better understand the factors effecting performance of haptic displays in this application and to develop tools which may be useful to others during system development. At its conclusion, this research will yield the following primary contributions:

- A generalized methodology for developing path-following controllers for arbitrary dissipative passive haptic interfaces with or without axis-coupling actuators.
- A set of performance measurements that may be used to evaluate performance of synergistic path-following controllers.
- Data from both simulation and experiment which support the validity of the control methodology.
- Correlations between quantitative performance measures and qualitative measures of operator reaction, supported by human subject testing of a statistically sufficient scope.

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