Implementation of Arbitrary Path Constraints using Dissipative Passive Haptic Displays

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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, 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. Nominaliy, 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.

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
- 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 [1]. 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 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.

2.2.1 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.

2.2.2 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 [2], 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 [3].

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.
2.2.3 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 [4], 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 devices 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 affect 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.

3 Proposed Research

3.1 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.

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 2. 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.
3.2 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 a large-scale two degree-of-freedom device with a workspace approximately one meter square. It consists of a five-bar linkage and is actuated by a set of four electromagnetic friction clutches. See Figure 3. Two of the clutches directly couple each of the two main axes of the device (links A and B in the Figure) to ground. They are capable of slowing down these links, or totally immobilizing them. The other two clutches couple the two axes together, either directly or in an opposite sense through the geartrain at the center of the device. These clutches may transfer energy between the main links, or may couple them rigidly together. It is useful to note that PTER is fully dissipatively passive, containing no energy storage elements. All motive power must come from the human user.

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.

3.3 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.

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.

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.

Proposed measures include path error, path error derivative, average jerk, average force, and time-to-completion. These separate, quantitative 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 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.

4 Human Subject Testing Protocol

This section details the actual human subject testing that will be performed during the course of this research. The goal of the testing is to obtain empirical data that will be useful in evaluating the performance of the developed control systems, as well as the inherent capabilities of dissipative passive displays to carry out path following tasks. In addition, correlations between the users’ mental evaluations of the performance of the device and physical measurements will be sought.

A full performance evaluation would not be possible without the use of human operators, as they are an integral part of the control system in any haptic display. The state of the art in human modeling, especially
dynamic behavior, does not have sufficient fidelity to accurately predict a user’s performance in carrying out
a path following task.

4.1 Subject Population and Briefing

Subjects will be healthy adults of both genders who have limited knowledge of the research being conducted. While the ultimate goal of the research will be explained to them, they will not know details of the data being recorded or the methods of analysis. Subjects will be recruited through undergraduate classes or through flyers posted in the ME buildings on campus.

It is anticipated that approximately 15 subjects will be required to obtain statistically significant data. After 5-7 subjects have been tested, a preliminary analysis of the data will be performed, and power analysis will be used to adjust the estimate of the required population size.

Before testing begins, subjects will be given a copy of the Consent and Release form (located at the end of this document), which will be fully explained to them. The subjects will have ample time to ask questions about the testing. The testbed’s construction and operation will be fully explained to them.

4.2 Physical Environment and Subject Safety

As mentioned above, PTER will be used as the haptic testbed for these experiments. PTER is currently located in a lab environment, and it may not be moved, as it is very heavy and requires sturdy mounting hardware. As the lab is used for other research, there may at times be other students working on other projects in the room. To minimize distraction, the subjects will be isolated to the area around PTER by cubicle dividers, and depending on the noise level in the lab, may be asked to wear headphones through which white-noise is played.

The only possible foreseeable physical risk to the subjects is fatigue. PTER is a large device and can exert relatively high forces on the user. These can be fatiguing over the course of using the device for 30-45 minutes, which is the envisioned duration of the testing. Users will be informed that if they feel tired or are in pain at any time to let the experimenter know, and the testing will be stopped immediately. Any users that have suffered from repetitive strain injuries, have arm or back problems, or have any other medical condition which may put them at higher risk of fatigue or which may taint the results will be excluded from participating. Before the testing phase of this research commences, the researchers will perform some tests using themselves as subjects in order to evaluate what levels of activity and duration of testing are appropriate to minimize the risk of fatigue.

Even though PTER is capable of exerting relatively high forces (on the order of 100 N) the forces are of a dissipative nature. That is, they will serve to remove energy from the system. Even when using the coupling actuators, energy is merely transferred between links of the device. This means that the system, even in the event of a controller or hardware failure, is physically incapable of producing forces that add energy to the system. All additive motive energy must come from the human user. There is no danger of the device going unstable and injuring the user with an uncommanded motion. Given this situation, the tests involving PTER should be classified as low-risk.

While the device is capable of exerting forces on the order of 100 N, this magnitude of force will not be exerted continuously. That is, the device is able to exert such forces momentarily in order to make corrections to the user’s motion. The aim of the device is to allow the user as close to free motion as possible, adding corrective forces when required to guide or communicate information about the environment to the user. Normally, the user will exert on the order of 1 pound of force continuously in order to move the device.

In addition to the goal of allowing the sensation of free motion, the device and its electronic controller are designed to be as “smooth” as possible. Smoothness is an elusive characteristic to measure, and such measurement is a goal of this research; however, a primary assumption is that smooth operation requires gradual changes in control inputs to the device. If a clutch is suddenly actuated with a high force, it will create a jerky sensation—not a smooth response. The control system will be designed to reduce abrupt changes in control activity as much as possible. Some tests will be done with purposefully non-smooth control techniques for experimental control and comparison purposes, but the level of abruptness in changes of system input will be such that it will effect user performance, but will be in no way harmful to the user.
4.3 Specific Tasks to be Performed

The subjects will be asked to perform several line-following and point-to-point motion tasks with PTER. This consists of attempting to move PTER along a defined line or attempting to move it from a starting area to an ending area. In some tests the subject will be informed of what the controller is trying to accomplish (i.e., guide user towards a certain point or constrain motion to a line in the workspace), while in others the subject will be asked to perform the task without being informed of how the controller will operate during the test. In some cases the control system will not be active, and the user will be free to move the device without outside intervention.

Visual feedback will be provided by a laser pointer mounted on the tip of PTER and a replacable template which may be placed on the floor underneath PTER’s manipulator. The laser pointer will be oriented so that it points straight down and projects onto the template. Depending on the task, start and stop areas, desired paths, and/or obstacles will be on the template. In path-following tasks, the user will be asked to guide the laser point along the desired path on the template. In point-to-point motion tasks, the user will be asked to start in a start box and guide the laser point into an ending box, possibly while avoiding obstacles displayed on the template.

Sets of tests will be designed for each type of task for different workspace configurations, different controllers, and different controller parameters. Subjects will be asked to perform multiple tasks, which will be chosen randomly from the set of possible tests. Several training tasks will be performed before data is collected. It is envisioned that each subject will perform approximately 30 tasks. This number will be driven by fatigue levels and available time, and will be adjusted based on preliminary data taken using the researchers as subjects.

4.4 Data Collection and Analysis

Physical data during the tests will be collected by PTER’s control computer. This will include positions and velocities of PTER, a history of commands sent by the control system, and a measure of the force exerted by the user. Milestone times during testing will also be recorded. All data sets will be identified by code number, and a record of code numbers and subject names or identifying properties will not be kept. The only identifying data that will be recorded with the code numbers will be gender and age. Other than through gender and age, there will be no way to identify to which subject a particular coded dataset belongs.

In addition to physical data, survey questions will be given to the subjects during and after the testing. The NASA Task Load Index (TLX) will be used to measure user workload and fatigue. This is a well-established survey, and is used widely in the field. Also, a survey developed by the researchers will be given. This survey will involve the user’s perceived performance of the device, and will ask the user to rate along a continuum the performance of certain configurations/controllers in several qualitative categories, such as smoothness, accuracy, speed, level of exertion, etc.

Data will be analyzed using standard ANOVA methods in order to look for correlations between physical data and the survey material. The bulk of the results that will be reported in the PI’s doctoral thesis and in any publications will be statistical measures. A select number of individual datapoints may be reported to illustrate outliers, unusual findings, or the like, but in no way will individual subjects be able to be identified.

5 Conclusion

5.1 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.
References


