N95- 14058

IMPLEMENTATION OF A THREE DEGREE OF FREEDOM, MOTOR/BRAKE HYBRID FORCE OUTPUT DEVICE FOR VIRTUAL ENVIRONMENT CONTROL TASKS

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The advent of high resolution, physical model based computer graphics has left a gap in the design of input/output technology appropriate for interacting with such complex virtual world models. Since virtual worlds consist of physical models, it is appropriate to output the inherent force information necessary for the simulation to the user. The detailed design, construction, and control of a three degree freedom force output joystick will be presented.

A novel kinematic design allows all three axes to be uncoupled, so that the system inertia matrix is diagonal. The two planar axes are actuated through an offset gimbal, and the third through a sleeved cable. To compensate for friction and inertia effects, this transmission is controlled by a force feedforward and a closed force feedback proportional loop. Workspace volume is a cone of 512 cubic inches, and the device bandwidth is maximized at 60 Hz for the two planar and 30 Hz for the third axis. Each axis is controlled by a motor/proportional magnetic particle brake combination fixed to the base. The innovative use of motors and brakes allows objects with high resistive torque requirements to be simulated without the stability and related safety issues involved with high torque, energy storing motors alone. Position, velocity, and applied endpoint force are sensed directly. Different control strategies are discussed and implemented, with an emphasis on how virtual environment force information, generated by the MIT Media Lab Computer Graphics and Animation Group BOLIO system, is transmitted to the device controller.

The design constraints for a kinesthetic force feedback device can be summarized as:

How can the symbiosis between the sense of presence in the virtual environment be maximized without compromising the interaction task, under the constraints of the mechanical device limitations?

Research in this field will yield insights to the optimal human sensory feedback mix for a wide spectrum of control and interaction problems. A flexible research tool that is designed as an easily reproducible product prototype has been constructed to explore the variety of possible force interaction.

Introduction

The advent of high resolution, physical model based computer graphics has left a gap in the design of input/output technology appropriate for interacting with such complex virtual world models. Visual display technology has improved dramatically, driven by developing communication through the most information rich sensory channel. Advances in stereographic displays and more proprioceptive input devices that contain higher degreee of freedom position information, such as full hand or body gesture recognition, still rely only on the visual sense. The user operates in a world of relative paralasys, not able to feel, grasp, touch, smell, or poke the objects that she interacts with.

Since virtual worlds are based on physical models, it is appropriate to output the inherent force information necessary for the simulation to the user. Before one commits large resources to the construction of such force output machines, the appropriate design constraints and problem definitions for simulated environment interactions must be addressed. The problem can be summarised as:

How can the symbiosis between the sense of presence in the virtual environment be maximised without compromising the interaction task, under the constraints of the mechanical device limitations?

Research in this field will yield insights to the optimal human sensory feedback mix for a wide spectrum of control and interaction problems: telepresence and supervisory control in remote manipulator tasks, advanced computer assisted engineering design tools, and surgical or flight simulators among many others. A flexible research tool to explore the variety of possible force interactions and is nevertheless designed as an easily reproducable product prototype has been constructed.

Overview and Design Specification

Traditional force output devices have concentrated on large, global movements, motivated by the scale of the teleoperated robot motion. In general, an analog slave sensor feedback signal servos the master joint motors. The geometric configuration and physical dimensions of the controlled manipulator and of the master are the same. In many cases, however, geometric equality is not necessary and can even hinder a particular successful task completion. Recently, in the flexible, unspecified tasks that are possible with virtual environments, the goal is to design the force output device so that its own dynamics are transparent and yet also can simulate as wide a frequency band of forces as possible. The range of motion used in interacting with a computer can be limited to a small surface or volume, one need only think of the small "mouse" interface device movement. The design of a force output device for virtual environments should maximize the device fidelity under the general constraints of size, cost, limited computation speed, and safety. These are the general constraints that drove the design of the presented force feedback interface. The design catagories are detailed below.

Design Categories:

Engineering Development:
- Design Simplicity:
  - Appearance
  - Limited Size
  - Robust
  - Versatile
  - Modular
  - Expandable
  - Safety
- Difficulty of implementation
- Technological base
- Cost

Controllability:
- Interface Transparency:
  - Can be counterbalanced (Electronically or Mechanically) Backdrivable
  - High DOF
  - Uncoupled axes
- Low degree of computation:
  - Full State measurement
  - Integrated into system w/o control/graphic display interference
  - Limited control logic
  - High Position Resolution
  - Uncoupled axes
- Closed or open loop control:
  - Full State measurement
- Stability:
  - Stiff
  - High natural frequency

Human-Device Interaction:
- Secondary Function Control
- Non-fatiguing
- Safety
- Human arm limitations never exceeded
- Interface Transparency
- Variable force feedback ratio

The described force output joystick incorporates linear but no rotational force output. Many manual tasks in which force information is of utmost importance and that are completed with the use of tools can be limited to three linear degrees of freedom. The metaphor used as a design guideline, which allows for a tractable problem within the design requirements, is a tool endpoint force simulator. To maintain design simplicity and limit the size without compromising device versatility, the joystick endpoint is limited to the three degrees of linear motion. It can be upgraded to include a small three degrees of freedom torque output mechanism, so a full 6 degrees of freedom force and torque output could be realised.

Any point contact can by modulated according to the characteristics imposed by the simulation. The joystick endpoint is a single probe with which to explore the virtual computer space. How effective such an approach is in transmitting tactile information is a matter of ongoing research (Minsky). Full, high resolution tactile displays have a large number of independent degrees of freedom, determined by the size and resolution of the display. Each tactile "pixel" must be independently controlled, so devices of this kind are difficult to implement. Examples include Braille machines for the blind, which are the state of the art for such devices, and it is an open question if their resolution is sufficient for effective, more general representation tactile displays.

A fine tool is not grasped with the whole hand, but rather like a pen between one's fingers. The force magnitude in such and interaction is much lower than in full arm movement. The restriction to finer forces and motions, which is appropriate for the limited workspace requirement of the human arm and hand, allows the joystick to be constrained in size since the actuator brakes and motors can have lower torque ouputs. Also, the smaller motors more easily meet the safety requirements and the limitation to three degrees of freedom decreases the difficulty of implementation and cost. The three degrees of freedom can be chosen such that the axes are perpendicular and all the actuators are attached to ground, thus eliminating cross coupling between the endpoint principal directions and the actuator torques. Rotary, no torque, ripple, low inertia motors and proportional magnetic particle brakes with a simple cable transmission for the third axis, and most of the sensors are readily available from existing technology. Only a three axis linear load cell of sufficiently small size and mass had to be specifically designed and constructed.

Control Requirements

The detailed mechanical design of the joystick is dominated by the control requirements of the simulation. To both impose the arbitrary simulation dynamics onto the joystick endpoint and minimize user fatigue when the joystick is used as a simple position input device, the actual characteristic or plant dynamics should not interfere with the simulation. This interface transparency is from the perspective of the user interacting with the joystick. One input to the plant is the force exerted by the user on the endpoint. The simulation, however, controls the desired dynamics through the input signals to the motors and brakes. The control strategy needs to maintain the simulation dynamics under varying user force inputs, or under the changing coupling characteristics between the user's arm and plant dynamics. The simulation essentially modulates the brake and motor signals so as to match the endpoint impedance or effective mass, stiffness, and damping characteristics to that of the virtual dynamics. The mechanical design maximizes the inherent device transparency and so minimized the control effort needed to backdrive the joystick. It has a bandwidty of 60 Hz for the gimbal driven axes and 30 Hz for the cable drive. Because of closed loop force control stability issues, open loop backdriveability is obtained wherever possible. This necessitates a direct drive between the brakes, motors, and joystick endpoint to minimize stiction, viscous friction and effective actuator inertia, which are all amplified by a transmission ratio. Direct drive in turn requires large motors for a significant torque. All the motors and brakes are fixed to ground and thus their weight and reaction torques need not be compensated for. Because of the much higher torque output of the brake for a given size and power input, any high torque requirements of the simulation will be met by the brake, an inherently passive, no energy storing and therefore safe torque device. Thus, both backdriveability and output force are maximized within the size and safety constraints.

No known research has been conducted in the appropriate strategy for hybrid, independent proportional brake and motor control. This novel combination promises to yield new methods of increasing stability and safety bound in actively controlled mechanisms without decreasing the closed loop device stiffness. The control of brakes necessitates a direct measurement of the contact force between the endpoint and user. Both for this reason and to actively backdrive the R-axis transmission, a loadcell 3-axis force sensor is implemented in the device.

The actual joystick endpoint position, velocity, and force are necessary to determine the characteristics of the interface dynamics. The servo loop sampling frequency is limited by the bandwidth of the simulated environment. As all the joystick control must operate in real time, the degree of computation lag in the control loop must be minimized. To achieve this and to eliminate quantization and noise errors at low velocities introduced by digital differentiation, both motor/brake shaft position and velocity are measured directly. The endpoint position and velocity can then be found through a simple matrix position and Jacobian transformation. The joystick linkage is chosen such that all actuator induced endpoint velocities are perpendicular. The axes are therefore uncoupled and any actuator exerts a force in one of the endpoint principle directions. The system inertia matrix is thus only diagonal, though time variant.

Future Work

Some simple texture and object simulation code has been implemented successfully. Present research efforts are concentrated on expanding the complexity of a real-time virtual world interaction by utilising the physically based graphics animation package in the MIT Media Lab Computer Graphics and Animation Group. Various studies of the effect of multiple sensory interaction on realism in simulations and the associated mechanical device complexity cost are proposed, with the present device as a research tool to quantify the effect of force information in successful task completion and enhanced apparent realism.