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# A HIGH PERFORMANCE TWO DEGREE-OF-FREEDOM KINESTHETIC INTERFACE

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## ABSTRACT

This summary focuses on the kinesthetic interface of a virtual invironment system that was developed at the Newman Laboratory for Biomechanics and Human Rehabilitation at M.I.T. for the study of manual control in both motorically impaired and able-bodied individuals.

## MECHANISM DESIGN

The kinesthetic interface is an electromechanically actuated manipulandum (*i.e.*, backdriveable manipulator) that enables dynamic interaction between the arm of a human operator/experimental subject and controlled mechanical loads. The manipulandum, depicted in Figure 1, consists of a direct-drive handle linkage which is coupled to two printed armature brushed DC motors. The interface is instrumented to sense displacements, velocities, and accelerations at the motor shafts, and forces between the hand grip and the linkage.

The coupling mechanism that joins the handle to the motors forms a spherical closed-chain five-bar linkage, resulting in two kinematic degrees of freedom at the hand grip. This linkage permits both actuator housings to be anchored to a common mechanicsl ground, thereby making it unnecessary to carry their excessive weight and inertia. Because the linkage consists of only ball bearing revolute pairs and rigid links, undesirable friction, backlash, and compliance characteristics associated with other transmission types are greatly reduced in this interface.

Additional attributes of this mechanism configuration prove advantageous for manipulandum control. Over its 17 cm square workspace, the interface is approximately planar, and, most importantly, the actions of the two motors are nearly decoupled.

## SYSTEM CONTROL

The overall virtual environment system, shown in Figure 2, consists of the kinesthetic interface and a planar video display. System operation is supervised by an LSI-11/23 based micro computer, responsible for collecting and storing data, commanding and monitoring the Control Interface Unit (CIU), and transferring target and tracking response information to the Amiga 1000 personal computer for display to the subject. The CIU contains hardwired circuitry to control load simulations by each motor as well as maintain system safety.

Because of the manipulandum's nearly planar and nearly decoupled linkage kinematics, configuration space control can be used to regulate endpoint impedance directly, *without* geometric computation. As a consequence, the LSI-11/23 host can update CIU load control parameters at rates exceeding 1 kHz.

## MECHANICAL LOAD AND OBJECT SIMULATION

The manipulandum's ability to produce positive (*i.e.*, resistive) and negative (*i.e.*, destabilizing) spring and damping fields was examined. Load ranges achieved with the CIU's hardwired digitally-supervised analog controller are listed in Table 1. Greater stiffness—up to 3 times higher—are obtainable under purely digital control implementations.

| Load Type | Rotational | Translational Equivalent |
|---|---|---|
| Active Resistive Stiffness | 0–136 N-m/rad | 0–3100 N/m |
| Active Resistive Damping | 0–6.7 N-m/rad/s | 0–152 N/m/s |
| Active Inertia | .007–0.045 kg-m$^2$ | .13-1 kg |
| Maximum Torque/Force | 4.7 N-m | 21 N |

Table 1: Load ranges achieved under digitally supervised analog control. The translational load equivalent is calculated for the hand grip end of the fixed length handle.

In addition to simulating mechanical impedances, the controller can either mask or enhance the manipulandum's passive inertia and friction, thereby allowing the handle to feel "invisible" when pushed and have sufficient friction to stay in place when "let go" by the human operator. Contact with a hard non-sticky wall anc capture by a detent also have been simulated convincingly by the manipulandum, as illustrated in Figures 3 and 4. Together, the performance capabilities described in this paragraph successfully meet a set of criteria used in the industry to demonstrate that an "artificial control feel" device is versatile enough to faithfully execute *any* general simulation (Jex 1988).

## REFERENCE

H. R. Jex. Four critical test for control-feel simulators. *Proceedings of the 23rd Conference on Manual Control*, Cambridge MA, June 1988.

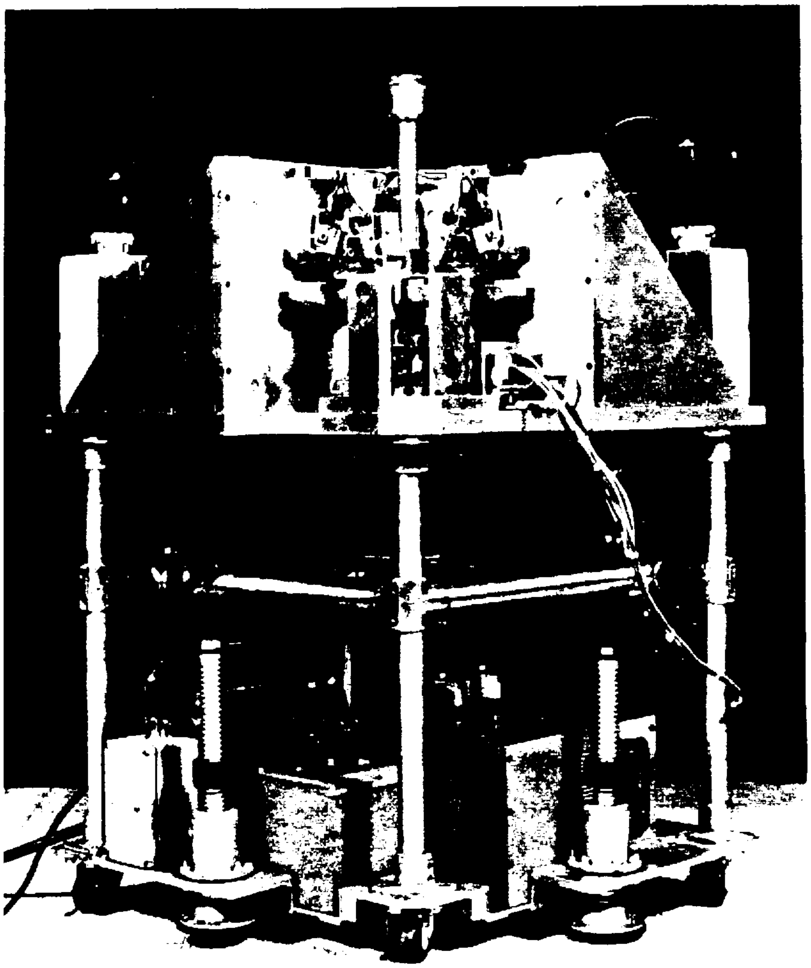

Figure 1. The manipulandum. Height from floor to spherical hand grip is 1 meter.

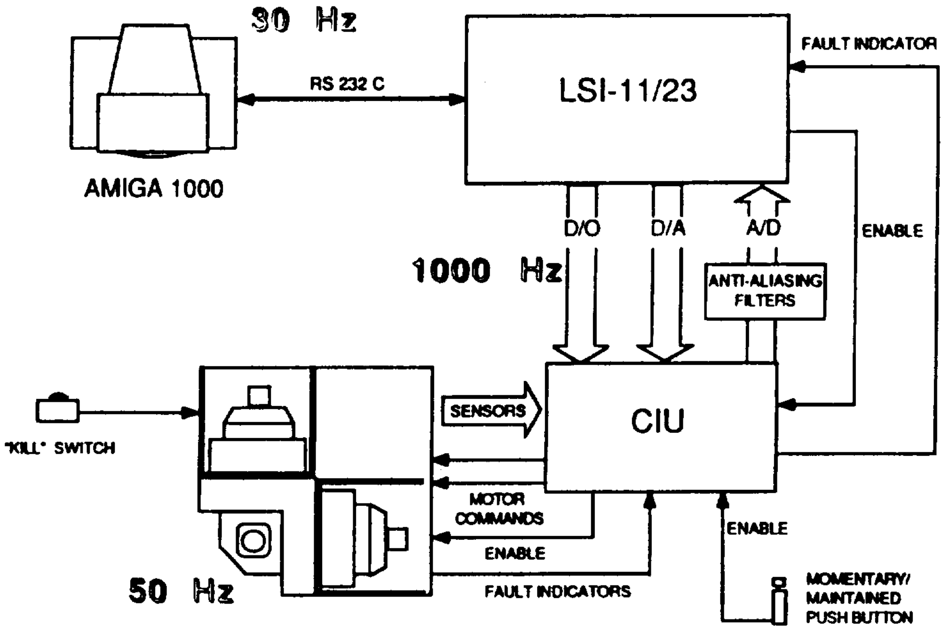

Figure 2. Virtual environment system components and communication. The highlighted frequencies (*clockwise from upper left* ) indicate the computer update rates for the visual display and load controller, and the manipulandum force bandwidth as determined by its first structural mode.

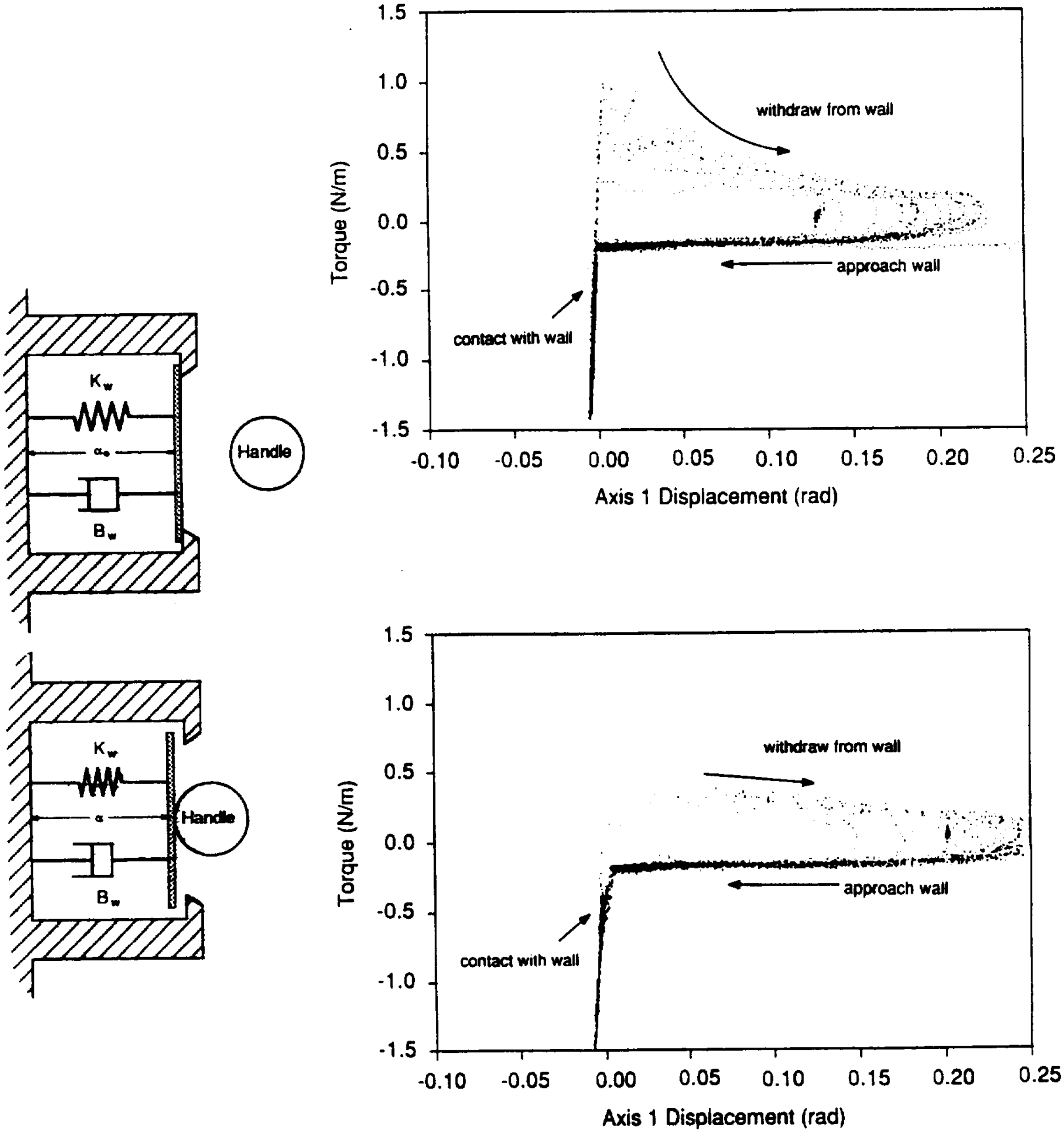

Figure 3. Wall model and implementations. The wall is modelled (*left*) as a massless plate backed by a stiff spring and viscous damper. When the handle is to the right of the wall rest position (*top*), no resistance is encountered. As the handle moves past the wall rest position (*bottom*), the spring and dampers oppose further motion to the left. Torques resulting from the hand force applied to the constant length manipulandum handle are plotted against displacement (*right*) to demonstrate the effect of bandwidth on wall quality. The upper plot shows wall performance with a 20 msec lag introduced prior to detection of the handle position by the computer. The lower plot has this lag removed. Both simulations are updated at 1kHz. The lag causes a perceived "stickiness," visible in the upper plot as the attractive force pulling the handle back toward the wall (*i.e.*, displacement = 0). Away from the wall, the difference between mean force levels during approach and withdrawal motions is due to uncompensated friction.

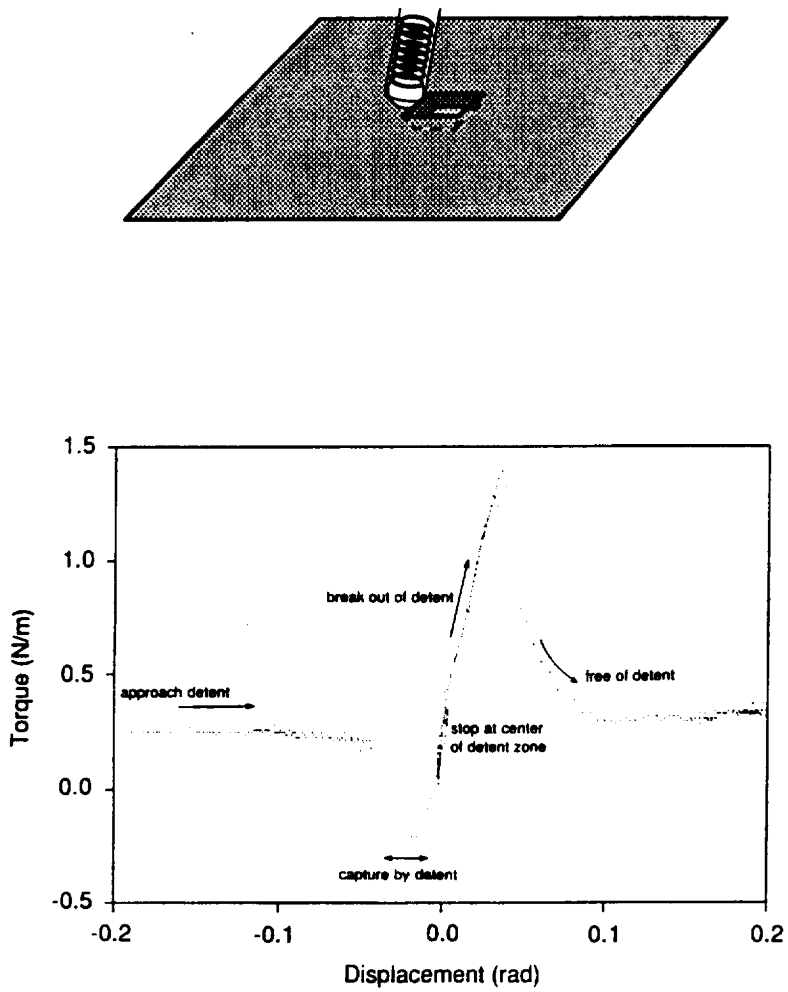

Figure 4. Detent model and implementation. The detent is modelled (*top* ) as a spring loaded ball plunger located at the bottom of the manipulandum handle that is trapped when it passes over the indentation in the planar workspace. The plot shows the history of torque due to handle force versus handle displacement in one of the manipulandum degrees of freedom as the handle is captured by a simulated detent, comes to a stop, and then breaks free.