The Touchback Keyboard

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ABSTRACT

A digital control system capable of simulating multi-degree-of-freedom dynamical systems in real time with visual, audio, and haptic displays is presented. A set of software and hardware tools form a testbed in which a dynamical system can be modeled, reduced to equations of motion, and simulated. The user interacts with a powered key to influence the behavior of the dynamical system and feel the computed interaction forces being fed back in real-time. Of primary interest for simulation with haptic display are the grand piano action and other keyboard instrument controllers. Various keyboard actions are demonstrated.

1. INTRODUCTION

Synthesis of not only the sound, but also the touch response of a musical instrument is made possible when a synthesizer interface contains actuators and control systems. Active (or even just programmable passive) components take the place of the 'mechanics' of the acoustic instrument (such as a piano action) while preserving the dynamical response characteristics or 'feel'. This design challenge has been taken on by researchers at several institutions, including ACROE [Cadoz 1990] and CCRMA, and independent inventors [Baker 1988]. A keyboard controller of this type can make various touch responses, such as those of a harpsichord, organ, or grand piano, available at the touch of a button. The advantages, however, go even beyond making synthesizers 'feel right'; the broader goal is to re-establish the touch relationship between performer and instrument.

How do we know, when we play an instrument, what effect our manipulations are having? Certainly we hear the response of the instrument; information flows from instrument to performer through sound. But with which additional senses do we follow the responses of an instrument to our gestures? The haptic senses: tactile, kinesthetic, force, proprioperceptive , etc. Unlike the audio, this mechanical channel allows bi-directional information flow. Since the only manner for the performer to communicate to the instrument is through manipulation by hand or mouth, these force/motion trajectories must transmit the performer's intentions to the instrument. Conversely, the reaction force/response motion history with which the instrument answers the input gesture is a signal containing valuable information about the instrument's behavior.

When, in addition to instantaneous force/velocity data, a force/velocity history is available, as is the case in the response to a gesture, the performer can perceive whether he/she is acting through an inertia, damper, compliance, or combination of these to excite sound vibrations.

We humans, equipped both with a means of manipulation and with haptic senses, are ideally suited to explore the 'physics' of our environments. In fact, processing feel information with the brain and using it to modify manipulation may be faster than processing and responding to audio information. [Phillips 1987]. We use such terms as 'look and feel' to refer to the response behavior of an interface to our input manipulations. An interface with a 'good feel' conveys maximum, even redundant information about the state of an application or whatever lies behind the interface. This allows a user to manipulate efficiently toward a given goal. Aftertouch on synthesizer keyboards is an example of an interface with no significant 'feel' feedback. There is no opportunity for the user to sense the state of the system except by listening. By contrast, a correspondence (not necessarily one-to-one) does exist between the touch-response and the sound of acoustic instruments. Although the haptic information may be redundant, it plays a vital role in processes such as learning to elicit desired tones.

The remainder of this paper introduces engineering language into the above discussion, then uses these terms to describe specifics about the touch-response of the grand piano and to outline specific design goals for a touch-programmable keyboard. Finally, a touchback keyboard prototype, useful for exploring these issues, is described.

2. MECHANICAL IMPEDANCE

The touch-programmable keyboard design challenge is similar in scope and make-up to that faced by designers of telerobots with force-reflection and haptic display devices for virtual environments. Motorized manipulanda relay a range of mechanical information either from the physical environment in which the slave manipulator operates or from the simulated virtual environment. There is a rich and growing body of literature in the field of robotics which can be profitably drawn upon. [Millman and Colgate 1991]

The performer and instrument are dynamical systems made up of inertial, damping and compliant elements, and, in the case of the performer, active elements. These two systems may exchange energy through an interaction port when contact is made between them. An equivalent passive impedance (frequency generalized resistance to force) may be substitued for the instrument. This manner of decomposition is completely analogous to techniques commonly used in circuit analysis. Whatever mechanism might lie behind a key, its influence on the 'feel' can be replaced by an instantaneous effective inertia, effective damping, and effective compliance at the key. The instantaneous reaction force that one feels is completely specified by three proportionality constants, one each for acceleration, velocity, and position. The only extension needed (in order to cover cases in which contacts are made and broken between various members of the mechanism) is to allow these three parameters to take on a configuration dependence. That is, because various sets of kinematic constraints are operative at various positions of a piano key, various inertial, damping or compliant elements will be active, or their effects reflected through various sets of lever arms.

3. THE FEEL OF THE GRAND PIANO

The following types of behavior characterize the piano feel and serve as targets for the design of a touch-programmable keyboard. First, the impedance of the piano action is dominated by the inertia of the hammer because of the catapult-like function of the action. There is an approximately 5-times mechanical advantage of the key over the hammer. Along with this inertia force, the performer feels a constant return force due to gravity acting on the hammer and key, called the ‘static imbalance’. When the instrument is played slowly, a dissipative force becomes apparent just before key-bottom, called ‘let-off resistance.’ This behavior results from friction between the jack and hammer knuckle as they slide against one-another during let-off. Finally, it is desired to re-create the repetition capabilities of the grand piano in the touch-programmable keyboard. The performer should be able to bounce a virtual hammer and feel the set, and then the re-trigger function of the repetition lever and jack at work.

4. DESIGN GOALS

The physical portion of the interface, the key and connecting actuators, are subject to the following design guidelines. To provide the performer with maximum sensitivity to variation in the level of computed force, the physical device itself must exhibit low inertia. To avoid increasing force thresholds and degrading force resolution, it must have low friction. To avoid adding unwanted compliant-behavior dynamics and to side-step potential control instability problems, the device, including its drive train, should exhibit high stiffness. The device must be highly back-driveable and have little or no backlash. The range of forces should be matched to human capabilities if the keyboard is to serve as a general experimental device, or, if it is to emulate existing instruments such as the piano, be matched to these. Whether the keyboard should be capable of simulating hard surfaces by active means or by passive means should be carefully considered because such simulations place very high demands on the maximum available force, the servo rate, and the controller robustness. The range of motion can be physically limited yet, in some sense, be made programmable by industrious design. Finally, a most exacting requirement arises with regard to size and weight. The physical device must be portable and wieldy. To be added to the list of design goals before this device hits the market, is cost.

5. THE TOUCHBACK KEYBOARD DESIGN

The present prototype meets only a subset of the above design goals, but does provide a useful testbed for exploring various control algorithms. A keyboard of eight keys has been constructed. Each key is coupled stiffly to its own voice-coil type linear motor, originally designed for use in large disk drives. Because these motors are somewhat oversized and of rather high inertia, one version of the interface is scaled up in size to a carillon keyboard to be played with the hands instead of a piano keyboard to be played with the fingers. Each motor is in turn driven by its own independent voltage controlled current amplifier. A 40386-based PC plays host to an eight-channel DSP motor control card containing all the necessary D/A, A/D and de-code hardware. The keys themselves are equipped with optical encoders, strain gages, and tachometers to sense position, velocity and performer/key interaction force. Knowing both the performer/key interaction force and the force applied by the motor to the key, the acceleration of the key can be deduced, providing a more accurate estimation of the actual acceleration than measurement with an accelerometer or differentiation of the velocity signal. The control loop can be closed either in the DSP chip itself, if speed is needed, or in a C program on the ‘386 cpu where the logic and control scheme design are very accessible. Various control schemes are being explored. For example, a description of the piano action in functional control blocks and logic can become the basis of the control system architecture. Another approach involves first formulating the equations of motion from the mechanical description and then writing these into a controller based on a numerical integration scheme [Gillespie 1992].

6. CLOSING

A few of the analysis and design techniques which have proven useful in the field of robotics are being directed toward the touch-programmable keyboard design problem. If the synthesized sound is actively evolving, as is often the case on popular new patches, performer instrument interaction which involves energy exchanges in both directions offers exciting new musical composition and performance possibilities.

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