Chapter 7

Summary and Future Work

The work of this thesis was undertaken with the ambitious plan of creating a motorized synthesizer keyboard which would feel and behave like the keyboard of a grand piano. To a significant extent, we have accomplished this goal. We now have in hand a keyboard of seven keys which exhibits some important aspects of the dynamical response (in terms of both mechanical impedance and sound) of the grand piano. We have arrived at a unique position, ready to design and carry out psychophysical experiments which test the original hypotheses underlying our project —that appropriate force feedback from a synthesizer leads to increased potential for musical expression.

7.1 Looking Back

The path to our present position has included several steps, each of which occupy, in description, a chapter of this thesis.

Psychophysics

First, we placed our goals with regard to the role of force feedback and auditory feedback from a keyboard instrument in clear perspective. Design of a force-reflecting device for musical control entails many subtleties in a field which remains largely unexplored. We are interested in forging ahead in the field of haptic interface despite the fact that human processing of haptic information is not yet fully understood. Satisfactory conclusions have not been reached as to which, if any, of the variables which we utilize for analysis in our controller designs, such as force or velocity, are those sensed and monitored by humans. Many effects such as adaptation, learning, and attention shifts must also be considered in an analysis of the role of force feedback in a device for human use.

A discussion of psychophysical factors pertaining to haptic display of the dynamics of the piano action was undertaken in Chapter 2. Although pianists do not have independent control over intensity (loudness) and timbre (tone color) through the piano action, they do have independent control over the composite of these two coupled parameters and timing. It was suggested that one parameter might be *perceived* as another, and that this factor may be used to explain the piano's *perceptually* observed independent control of intensity and timbre and attendant unrestricted capabilities of musical expression. This hypothesis, if true, further motivates our goals of emulating the piano action's refined behavior in terms of hammer strike time and velocity and in terms of response forces using a keyboard-like haptic interface. After all, the response forces of the piano action are an integral component of the piano's behavior since the piano action and user constitute a coupled dynamical system. Interaction forces are part and parcel of that coupling and therefore come into play in the mapping from gesture to hammer strike parameters (or equivalently, from gesture to sound parameters). An analysis based on the coupling of two dynamical systems is consistent with the viewpoint that the human is neither a force nor motion source, but more appropriately modeled as a time-varying impedance. The ultimate response of this coupled system depends on the dynamical properties of both subsystems, human limb and piano action.

Another explanation of the disappointing utility of standard synthesizer keyboards at controlling musical sounds was offered in Chapter 2, based on the controls engineering concepts of *controllability* and *observability*. Although the selection of the sound parameters of the piano (intensity/timbre and timing) is *possible* from a simple synthesizer keyboard outfitted only with two-position switches, that selection is not as intuitive or 'organic' as in the case of the piano action. The sensitivity and predictability of these parameters to variations in the control input and the wealth of information about the fine effects of the control input which are hallmarks of the piano action are not available from the standard synthesizer keyboard. In the context of control by a human user, it can be said that the synthesizer keyboard does not support or encourage the development of various techniques as does the piano action. In particular, localized impedance variations or haptic features (localized in space, in time or in the parameter space of the input gesture) such as arise in the response of a dynamical system with changing kinematic constraints (including the piano action) are useful for increasing controllability and observability for a human user. Such localized features increase the store of available techniques and further, provide clues and suggestions for the development of such techniques which are consistent with common haptic experience in the physical world.

Dynamics of the Grand Piano Action

Second, with the aim of eventually emulating the piano action using human-in-the-loop simulation, we built a dynamical model of the action using the most numerically efficient model formulation —a formulation in independent coordinates. Armed with efficient modeling methods and accompanying computerized tools (Kane's method and *AUTOLEV*), we did not have to balk at the challenge of formulating constrained multibody dynamical models of the piano action. We didn't even hesitate to use constraint equations which are subject to change in order to eliminate dependent coordinates from the model, as has been the predilection of most researchers modeling variable structure systems. To encode the dynamics of changing kinematic constraints, we built models of the action in each of its constraint conditions and outfitted these models with the requisite indicator functions which would allow them to be linked together interactively during run-time. We extended the simulation methods currently available for simulation of such discontinuous systems to include a finite state machine. The finite state machine enables the accommodation of run-time dependence of submodel sequencing on user input. 'Artificial constraints' were introduced and used to cause those generalized coordinates which were not needed in a particular constraint configuration to nevertheless take on dependencies on other coordinates so that, when a time would arrive to exchange submodels in the simulator, the final conditions of that submodel could be passed on as initial conditions to the next, without risking violation of newly instated constraint equations. Details of the simulator software architecture were presented in Chapter 3, along with simulation results which verify that the effects of changing kinematic constraints on both the mapping from gesture to hammer strike parameters and the mechanical impedance of the piano action were successfully captured. 'Regulation' of the virtual piano action model is now possible with stop-button screw adjustments which fully parallel its referent, making fine tuning of behavior relatively easy —though probably still to be relegated to specialists. Piano technicians will certainly not be displaced with the rise of the virtual piano action.

Touchback Keyboard Design

Third, we built the haptic interface itself, which was featured in Chapter 4. An aluminum key, capstan-driven by a small high-performance motor through a 24:1 mechanical advantage, was designed to display, in the unpowered state, the impedance of a wooden piano key without the lead weights. Thus the controller driving the motor would be responsible for re-creating the dynamical effects of all elements of the piano action except the wooden key. The novel mechanical design of our keyboard which allows for the packing of all components into the tight space determined and enforced by the piano key spacing was documented. The piano action models built for simula*tion* in Chapter 3 were re-interpreted as controllers for the haptic interface, thus realizing a piano action simula*tor*. Sensed position is fed into the controller which responds with a torque to be displayed by the haptic interface. A parallel spring-damper pair is used to couple the physical hardware to the forward-dynamics simulation. This impedance-display implementation was contrasted to other possible implementations, including admittance-display.

Improved Controllers for the Virtual Wall

Certain destabilizing effects which tend to evoke non-physical behavior from simulated objects are particularly apparent with haptic display. Virtual objects with changing kinematic constraints are prone to contact instability, or chatter. Such chatter, being very uncharacteristic of real world objects will, upon encounter, immediately expunge any sense of virtual environment immersion which the user may have been enjoying. Contact instabilities and similar phenomena can be attributed to the fact that a virtual object's mechanical properties are simulated within a feedback controlled system in discrete time and mediated through a powered device. Virtual walls, for example, despite the fact that they are the simplest of objects containing a changing kinematic constraint, will exhibit contact instability (observed as sustained oscillations between contact and non-contact with the virtual wall) given certain parameter settings: high gains or low sample rates. Two insidious destabilizing effects are due to the zero order hold (a necessary element in any sampled data implementation) and what we have termed intersample threshold crossing (an artifact of the wall controller's switching nature and its sampled data implementation). Both of these effects can be quelled, however, using an assumed model of the full coupled system (which includes the human). Compensation for the effects of the zero order hold relies either on half-sample prediction or full state feedback using pole placement techniques from digital control theory and an assumed model of the driven key and the human limb. Compensation for the effects of intersample threshold crossing is performed with the use of the assumed model and an application of dead-beat control.

When no volitional control is involved, the literature shows that the human finger may be modeled as a second order linear impedance. Using the fact that the oscillatory behavior suffered by virtual walls is typically well above the frequency range of human voluntary movement, we have used static second order models for the human in the design of our new interactive controllers. This move is new to the literature. We think, however, that such methods can be used to great advantage and with ample justification. We are using local (short time duration) techniques to quell destabilizing effects which arise locally. Most importantly, such ideas hold much promise in their extension, such as when on-line system identification methods are used to keep the human models continually up to date, as further discussed below.

Stability Analysis of the new Virtual Wall Controllers

The new virtual wall controllers developed in Chapter 5 were analyzed for their usefulness in Chapter 6 with analytical treatments. Measures for the destabilizing effects of the zero order hold and intersample threshold crossing were sought for use in determining the worthiness for implementation of the new control techniques. An analytical solution for the damping coefficient which will balance the destabilizing effects of intersample threshold crossing under worst-case and non-existent bias force from the human was presented. Numerical extensions of this analytical result were made with a Poincaré map which was also derived, verified, and demonstrated.

7.2 Looking Forward

Psychophysical Investigations

With our seven-key touch-programmable keyboard in hand, we are ready to design and conduct a set of psychophysical experiments which investigate the utility of force feedback in musical expression. Since the synthesizer keyboard proved incapable of the range of musical expression found on the piano keyboard, and this fact seemed to be due to the lack of piano-like touch-response and the inappropriate substitution of velocity sensitivity for the piano's multifaceted mapping from gesture to sound parameters, we went about outfitting a synthesizer keyboard with force feedback and running interactive simulations of a piano action. Now we have an apparatus which can be programmed with various relationships between the feel at the key and the sound-response at the speaker ("soundboard"). With such an apparatus in hand, we may test whether a varying mechanical impedance such as that of the grand piano will help a musician develop and execute the fine control over musical sounds at the synthesizer keyboard which he already enjoys at the piano keyboard. Beyond the question *whether*, questions such as *how* may be asked. If we may learn how a human uses their sense of touch to develop manipulation strategies, then the very exiting possibility of designing instruments with maximized controllability and expressive potential will be opened up for exploration. I look forward to collaborative work in this area with experimental psychologists and experts in psychophysics and haptics.

Touchback Keyboard Development

The supporting hardware for this thesis, the seven-key Touchback Keyboard, also has a natural extension —its commercialization. Synthesizers constitute a very large and lucrative industry today, and there exists a sizable market for high-end synthesizer keyboards which feature optimum touch-response. The digital piano and synthesizer review-articles which appear at least annually in each of the electronic music magazines invariably claim that touch-response is the second most important factor for the buyer's consideration after sound quality. These reviews usually include tutorials on synthesizer actions and offer detailed critiques of how close the various presently available passive synthesizer actions come to duplicating the feel of the grand piano action.

Another testimonial to the viability of a touch-programmable keyboard-as-product is the interest with which each of CCRMA's industrial affiliate companies has been following this thesis work. Representatives from a number of synthesizer controller manufacturers, including Korg, Roland, Yamaha, and ZETA have been hearing about our work through CCRMA's industrial affiliates talks each year and have offered enthusiastic comments and support. This project is of course indebted to the industrial affiliate member companies since they have provided the financial support through the CCRMA affiliates program. Although the present design has yet to be optimized, made robust, and made truly cost effective, I regard the commercialization of force feedback in synthesizer keyboards as inevitable. Furthermore, force feedback will be the means to make concert-quality musical instruments available to the general public. Haptic interface technology promises gains in cost-effectiveness and manufacturability, whereas the existing hardware-intensive piano action design will only meet with increased costs in future times.

Modeling and Simulation Extensions

Our basic method for re-creating the touch response of a grand piano in a motorized keyboard is through human-in-the-loop simulation. Each key is coupled through a virtual spring and damper to a forward-dynamics simulation of a piano action model. The spring-damper coupling method is simple and provides for the filtering of the driving input and the response forces of the piano action. Although the spring-damper filter robs the displayed dynamics of high frequency components (crispness), especially when kinematic constraints change, it serves the very important purpose of suppressing the destabilizing effects of discrete simulation. However, the use of the more direct inverse dynamics simulation for impedance display (when force is computed directly from the virtual environment model, rather than with the use of a spring-damper coupler) is now of interest. The suppression or prevention of destabilizing effects would perhaps be more appropriately applied closer to the source of these numerical woes, in the discrete simulation algorithm itself.

For example, analytical treatments of numerical methods have produced restrictions on the stepsize which guarantee that the asymptotic behavior of the underlying differential equation be replicated when those numerical methods are used to simulate autonomous systems. These stepsize restrictions are a function of structural assumptions on the underlying differential equation and sometimes on initial conditions. The extension of these parameter bounds to non-autonomous system simulation such as is employed in human-in-the-loop schemes would assure the absence of numerical problems in inverse-dynamics simulations. Note: this idea is closely related to that discussed below under the heading 'extensions beyond the virtual wall'.

Virtual Wall Extensions

The appearance of destabilizing effects in an inverse dynamics setting was fully explored in the case of the virtual wall in Chapter 5. The virtual wall is a static system, implementable with a control law rather than with a numerical method. The virtual wall, because of its simplicity, allowed us to thoroughly explore a central theme of this thesis: Having chosen to use a discrete controller to endow a simple manipulandum with the dynamics of a more complex dynamical system, the simulation is prone to certain non-physical effects. When and if the full closed loop system (including the human) can be modeled, these non-physical effects can be eliminated using methods from digital control theory. Extensions to this theme center around the words *when and if* of the previous sentence. After all, an assumed model of the dynamics of the human will only be valid for very short time durations (for durations so short that volitional control will not be involved). While haptically exploring the rendered virtual object, the human's impedance properties will change. Two extensions to the approach of assuming a model for the human are immediately apparent.

- The model could be kept up to date at all times by incorporating an on-line system identification method into the controller. The force and motion signals at the contact point between human and manipulandum could be monitored and used, along with the known virtual environment dynamics, to ascertain the impedance properties of the human. The interaction controller (virtual environment display) would be continually adapted using this up-to-date human model to ensure always valid compensation for discrete implementation effects.

- The exact model for the human could be broadened to a model only satisfying certain structural restrictions. These structural restrictions would be chosen to lend themselves to analytical treatment and the generation of guidelines for the simulation method. Appropriately restrictive, yet not overly conservative assumptions about the set of behaviors which the human may be expected to exhibit within the system could be used to come up with haptic interface device and controller design guidelines which would ensure passive behavior of a simulated object. One such restriction which has been explored in the literature, especially by Colgate, has been the restriction of the human dynamics to passivity. This restriction, however, might be regarded as overly conservative within certain bandwidths and not conservative enough in others. Other sets within which to bound the human are worth considering. We would, after all, like to allow the expression of intentions by the user through occasional active behavior, yet still provide assurance that the power exchanges between user and interface device will be those which suggest interaction with real-world objects. The set of behaviors within which the human is restricted (for purposes of analysis) could be conformed to sets inside of which he may be expected to remain due to the action of natural and pre-existing constraints. This set would be larger in some respects than the set of all passive behaviors but smaller in other respects.

Finally, an extension to the virtual wall controllers presented in this thesis which would be very valuable from an implementation standpoint will be the incorporation of a velocity signal which is derived by numerical differentiation from a position signal in place of the direct velocity signal. Many haptic interface designs do not include a tachometer or other direct measure of velocity. Instead they rely on numerical differentiation of an encoder reading. Colgate's passivity analysis of the virtual wall supports the empirically observed destabilizing effects of large gains on the velocity term when a first-differenced position signal is used. The stability treatments in this thesis will be generalized in future work to cover this important effect.

Extensions beyond the Virtual Wall

The methods for the abolition of non-physical discrete simulation effects as they currently stand apply only to the simplest of virtual objects, the virtual wall. Similar factors, however, also underlie the non-physical behavior of dynamical, or multi-degree-of-freedom objects with changing constraints such as the virtual piano action. A major goal of future research will be to develop robust methods for simulating *dynamical* virtual objects which realistically support changing kinematic constraints. This will involve the design of new simulation algorithms which, like the analytical techniques and resulting design guidelines pertaining to the virtual wall, make use of assumptions about expected human behavior.

Integrated Haptic Interface Device and Simulator Design

Another attack on the problems associated with interactive dynamics with haptic display could be made with special attention to the design and utilization of computing hardware. The notion of computing hardware in the field of haptic interface of course encompasses the interface device itself in addition to the computer. Hardware architectures as suggested by certain simulator structures could be explored, such as parallel processing. Shared simulation across networks for multi-user environments also deserves attention. Interface design and software design go hand in hand for effective haptic display, and further gains are to be expected when the modeling procedure itself is factored into the structure of the simulator and computing hardware. Device and actuator design is another area which must be driven, especially with an approach which integrates controller design. We have, as proof of existence of room for improvement, the consummate example of effective manipulation and interactive behavior in the human system itself. The human hand and arm along with their controller are obviously very successful designs. Although the goals of haptic interface technology are re-create the mechanical properties of environments rather than to directly manipulate, exceptional human performance still stands as a testimony to the advantages of co-evolved and co-designed controller and actuator.