A PHYSICALLY INTUITIVE HAPTIC DRUMSTICK

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ABSTRACT

We motivate and discuss the design of a physically intuitive haptic drumstick. A new musical instrument is physically intuitive if the physics of haptic interaction are similar to those supported by a traditional musical instrument. We suggest that physically intuitive new musical instruments may help performers transfer motor skills from familiar, traditional musical instruments. Both actively controlled acoustic instruments and many haptic instruments are physically intuitive. We design a physically intuitive haptic drumstick. Simple models of drumstick dynamics and drumstick/membrane collisions are explained and implemented on a high-resolution haptic device. Next, we create a new musical instrument by altering the haptic drumstick dynamics in a physically intuitive manner. We focus on drum rolls. In particular, we alter the haptic drumstick dynamics to assist performers in playing single-handed drum rolls. Finally, we analyze the stability of the altered system dynamics using a Poincaré map.

1. INTRODUCTION

Consider the differences between a professional new musical instrument performance and a professional violin performance. The violinist has had years if not a lifetime to master the motor skills used to play the violin. In contrast, the new musical instrument performer has perhaps learned foreign motor skills for a new interface under time constraints. While the learning process undoubtedly provides the new instrument performer with fresh ideas, he or she must largely ignore the vast portions of motor skills obtained while mastering other less relevant instruments.

Instrument designers can avoid handicapping new instrument performers by leveraging their prior motor skills. One possible solution involves designing interfaces supporting physical interactions that are already familiar to performers. We call such interfaces *physically intuitive*. This design criterion is similar to the common goal in haptics of using a haptic device to accurately simulate the physics of various real-world interactions. The haptics literature suggests that motor skills may be transferred from haptic interfaces to real-world situations when the physics of interaction are accurately modeled [7]. We are more interested in the reverse—the transfer of skills from a *traditional* musical instrument to a *new*, haptic musical instrument. We argue that the reverse should be plausible since neuroscientists believe that human interaction with objects is governed by internal conceptual physical interaction models [10]. Nevertheless, concrete experiments in learning musical instruments need to be carried out for verification. In the following, we discuss some kinds of new musical instruments that aim to promote skill transfer by virtue of their physical intuitiveness.

1.1. Actively Controlled Acoustic Musical Instruments

An actively controlled musical instrument is based upon a particular traditional acoustic musical instrument, whose structural acoustics are altered with feedback control so that the instrument sounds very different [3] [2]. Due to the physical constraints revolving around the traditional instrument, the physics of the performer's basic interaction with the instrument remain similar. As a consequence, the instrument is physically intuitive.

1.2. Physically Intuitive Haptic Musical Instruments

Haptic or force-feedback musical instruments have been in use since the 1970's if not earlier [4]. Such instruments can be programmed to exert forces on the performer depending on the performer's position in space. Within the limits of the hardware and software, any dynamical system can be realized. This seemingly limitless programmability of haptic instruments provides the musical instrument designer with considerable freedom. Perry Cook argues that "programmability is a curse" in this sense as it can distract musical instrument designers, and "normal humans" may find especially exotic instruments "frustrating, paralyzing, or offensive" [5]. We suggest that the new musical instrument designer may help mitigate the curse of programmability by considering physically intuitive haptic musical instruments, which support physical interactions similar to those that a traditional musical instrument supports. In the following sections, we explain the design of a physically intuitive haptic drumstick. We begin by designing a haptic musical instrument that behaves similarly to a standard drumstick and drum. Then we alter the haptic instrument slightly, creating a new haptic drumstick instrument that assists the performer in playing drum rolls while still remaining physically intuitive.

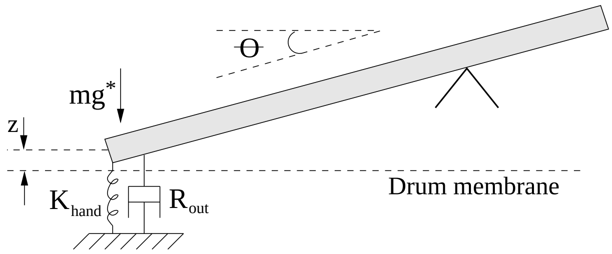

Figure 1. Drumstick dynamics for $z > 0$

2. MODEL OF DRUMSTICK DYNAMICS

Before designing a physically intuitive haptic drumstick, we need to develop a physical model of a drummer playing a drum roll. Consider the double stroke roll in which the drummer throws a stick at the membrane, allows it to bounce twice, retracts it, and then repeats the action with the other stick. The manner in which the drum membrane throws the stick back toward the drummer helps facilitate both the bouncing and retracting actions. Because we are concerning ourselves primarily with relatively fast drum rolls, we assume that θ does not change much (see Figure 1). This simplification allows us to linearize the rotation of the drumstick tip, and so we model the vertical motion of the drumstick tip as a bouncing ball with mass m. Given the rotational inertia of the stick and the position where it is held, it is possible to derive the equivalent mass m of the ball and gravity g^* such that forces on the ball can be mapped directly to forces on the tip of the drumstick.

2.1. Above The Drum Membrane

The hand grasping the stick acts as both a rotational spring and a rotational damper at the butt of the stick (not shown). For simplicity, we linearize these elements and commute them to the drumstick tip, representing them by K_{hand} and R_{out} (see Figure 1). By changing the grasp of the stick, the drummer can change K_{hand} and R_{out}. This is known as *passive impedance modulation* and allows drummers to play drum rolls at rates up to 30Hz, even though the human neuromuscular system has a reaction time of over 100ms [6]. By considering that the drummer may also adjust the rest position z_{h0} of the spring, in effect exerting a force on the stick, we may let $z_{ss} = z_{h0} - mg^*/K_{hand}$ and write the equation of motion in the absence of collisions with the drum membrane (i.e. for $z > 0$):

$$m\ddot{z} + R_{out}\dot{z} + K_{hand}(z - z_{ss}) = 0 \qquad (1)$$

2.2. Simple Collision Model

The physics-based approach to modeling stick/membrane collisions involves the coefficient of restitution (COR) β. For a collision beginning at any time t_{in} and ending at any time t_{out}, if $\dot{z}(t_{in}) = v_0$, then $\dot{z}(t_{out}) = -\beta v_0$. On the other hand, in haptics, the standard method for modeling a collision involves a spring-like penalty force implemented by a spring with constant $K_{coll} \gg K_{hand}$. There must also be some damping factor R_{in} due to losses absorbed by the hand and the collision, so we arrive at the dynamics for $z < 0$ (see Figure 2):

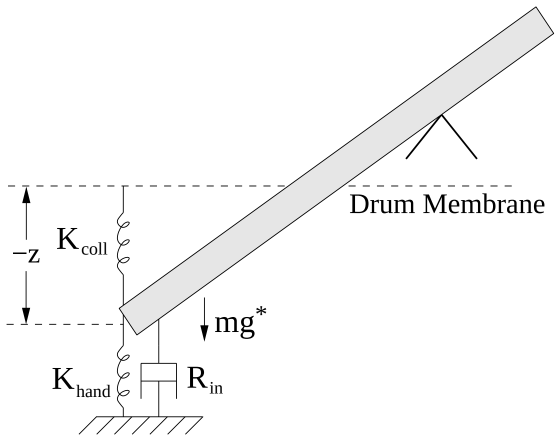

Figure 2. Drumstick dynamics for $z < 0$

$$m\ddot{z} + R_{in}\dot{z} + K_{hand}(z - z_{ss}) + K_{coll}z = 0 \qquad (2)$$

The term z_{ss} causes the COR β to become weakly dependent on the velocity $\dot{z}(t_{in})$ at the beginning of a collision. However, since the collision is quick, the terms involving R_{in} and K_{coll} dominate. Neglecting the other terms, we may solve the differential equation analytically to arrive at

$$\beta \approx \exp \frac{-R_{in}\pi}{\sqrt{4mK_{coll} - R_{in}^2}}. \qquad (3)$$

2.3. Upward Soft Collisions

Noting the similarity between (1) and (2), we suspect that we may also determine a COR α for the "soft collision" against the hand in the upward direction. However, since the spring constant K_{hand} is relatively small, the collision takes longer, and so we can no longer neglect z_{ss}. Consequently, $\alpha(\dot{z}(t_{out}))$ is strongly dependent on the velocity $\dot{z}(t_{out})$ at the beginning of each "soft collision," so the expression for α is more complicated than the expression for β. Nevertheless, in simulations of (1) for reasonable system parameters, we have verified that α remains roughly constant for bounces of similar amplitude.

3. HAPTIC DRUMSTICK

To construct the haptic drumstick we desire an appropriate haptic display for implementing the equations of motion. Haptic drumsticks have previously been implemented using single DOF haptic displays [1].[1] We use the three DOF Model T PHANTOM haptic device[2] because it has relatively strong motors—for moderately strong strokes, the motors are able to render stiffnesses comparable to a typical drumhead. The performer holds the drumstick-like

[1] http://web.media.mit.edu/˜grindlay/FielDrum.html
[2] From SensAble Technologies, see http://www.sensable.com.

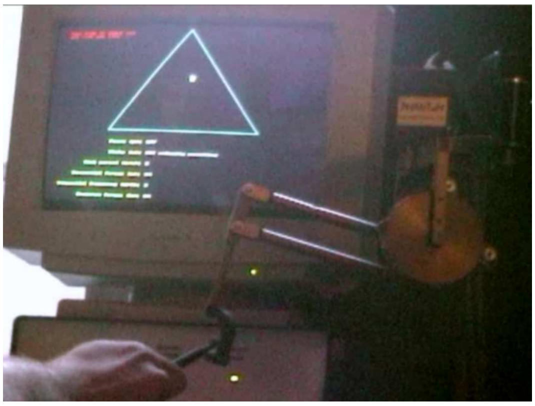

Figure 3. Graphical display (upper left) and PHANTOM robotic arm (lower right)

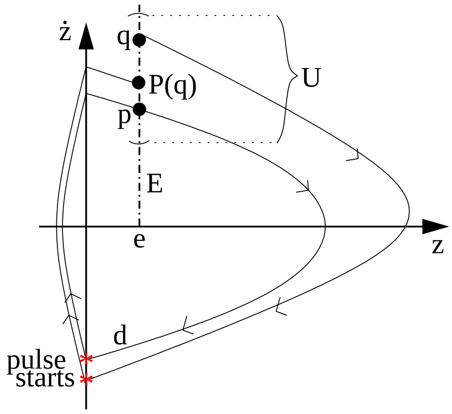

Figure 4. Example system trajectories and Poincaré map

stylus in one hand as shown in Figure 3. Using standard drumming techniques, he or she can for instance play a double stroke drum roll with the help of a traditional drum and drumstick controlled by the other hand (not shown). The sound synthesis engine consists of a digital waveguide mesh modeling waves propagating in a drum membrane [9]. The force of the drumstick on the spring K_{coll} is fed into the nearest node in the mesh. This way, striking the modeled drum at different positions results in different sounds. Note that the haptic forces are implemented by (1) and (2) do not depend on the sound synthesis engine. A video demonstration is available online. [3]

4. ALTERING THE DRUMSTICK DYNAMICS

There are many ways in which the dynamics could be altered. We consider alterations involving noise and deterministic chaos to be less desirable because they are not physically intuitive. In contrast, stable limit cycles, which are self-sustaining attractive oscillations, describe the behavior of biological oscillators such as the heart. Limit cycles also manifest themselves in bowed strings, vibrating reeds, and drum rolls.

Most drummers use two hands to play drum rolls. This limits the types of patterns that they can play. However, by inducing limit cycle behavior, we make it easy for a drummer to single-handedly play a drum roll. In informal tests, we determined that implementing system delay, a hysteretic spring K_{coll}, or negative damping R_{out} make the haptic drumstick more likely to self-oscillate, but not in a particularly physically intuitive way. Indeed, such mechanical elements do not occur readily in nature. A more physically intuitive solution involves forcing the drumstick in the positive z-direction by the pulse $h(t)$ every time the stick enters the simulated membrane, where

$$h(t) = \frac{m\Delta v_{pls}}{\tau} e^{-t/\tau} \quad (4)$$

and $\tau \approx 2$ ms. These force pulses are superimposed with the forces described by (1) and (2). Assuming a quick enough pulse, the pulse $h(t)$ causes the velocity of the drumstick tip to change by Δv_{pls}. Playing a drum roll with these altered dynamics feels somewhat like holding a stick against the spokes of a rotating bicycle wheel.

4.1. Directly Altering The COR

Since we can effectively change the velocity of the drumstick after the collision, by choosing $\Delta v_{pls} = -\gamma \dot{z}(t_{in})/\beta$ for some $\gamma > 0$, we can obtain a new COR $\hat{\beta} = \beta + \gamma$. With $\hat{\beta} > 1$, we can counter the damping due to the hand.

4.2. Applying Pulses With Constant Magnitude

Choosing Δv_{pls} to be constant presents a superior alternative because the total energy in the system becomes limited. This safety mechanism prevents drummers from inadvertently damaging the robotic arm. Consider that for vibrations at small amplitudes, the effective $\hat{\beta}$ is large, and that for vibrations at large amplitudes, the effective $\hat{\beta}$ is approximately equal to β. In the next section, we show that choosing Δv_{pls} constant leads to stable limit cycle behavior.

5. STABILITY ANALYSIS

5.1. Analysis

We analyze the altered dynamics with a Poincaré map, which allows the stability of a closed orbit in a continuous-time system to be determined from the stability of a related discrete-time system [8]. Let $\mathbf{z} = (z, \dot{z}) \in \mathbb{R}^2$ describe the system state, and let the *system flow* $\phi_t(\mathbf{z_0})$ describe the current state given an initial state $\mathbf{z_0}$ at t seconds in the past. Call d the periodic orbit of the system in the phase plane of $\mathbf{z}$, and consider the semi-infinite line E, which is crossed once per cycle by system trajectories (see Figure 4).

$$E = \{(z, \dot{z}) | z = e, \dot{z} > 0\} \quad (5)$$

For simplicity, we take $e > 0$ to be arbitrarily small. We assume that $z_{ss} < 0$ so that after leaving the mem-

[3] http://ccrma.stanford.edu/˜eberdahl/Projects/HapticDrumstick

brane, the drumstick will eventually strike it again. To simplify the analysis, we restrict U to be a small enough neighborhood of p on E so that α is approximately constant (see section 2.3). We further assume that the pulse $h(t)$ is short enough that it always ends before the trajectory intersects E. If we then define the map $P : U \rightarrow E$ so that for $q \in U$

$$P(q) = \phi_{\tau(q)}(q) \tag{6}$$

where $\tau(q)$ is the time for the orbit $\phi_t(q)$ based at q to first return to E, $P(\cdot)$ is a Poincaré map. Consequently, we may analyze the stability of the closed orbit d by analyzing the stability of the discrete-time system $P(v_i)$, where v_i is the velocity of the drumstick tip at the end of the ith collision with the drum membrane.

$$v_{i+1} = P(v_i) = \alpha\beta v_i + \beta\Delta v_{pls} \tag{7}$$

5.2. Directly Altering The COR

For the alteration where $\Delta v_{pls} = -\gamma\dot{z}(t_{in})/\beta = \gamma\alpha v_i/\beta$,

$$v_{i+1} = P(v_i) = \alpha(\beta + \gamma)v_i. \tag{8}$$

If the alteration of the dynamics is configured with γ such that $\alpha(\beta + \gamma) = 1$, then (7) describes a marginally-stable system, so the drumstick will oscillate at constant amplitude. However, this behavior is not stable—any parameter deviation will lead to a decaying oscillation or a growing oscillation. Since $P(\cdot)$ is a Poincaré map, the closed orbit d is an *unstable limit cycle*. Nevertheless, a drummer may stabilize this system by adjusting α in real time using passive impedance modulation.

5.3. Applying Pulses With Constant Magnitude

When Δv_{pls} is held constant, (7) describes a discrete-time linear system driven by a constant input. With the exception of the pulse $h(t)$, collisions with the membrane and upward soft collisions against the hand are dissipative. This means that $\alpha < 1$ and $\beta < 1$. Then $\alpha\beta < 1$, so (7) describes a stable discrete-time system. Since $P(\cdot)$ is a Poincaré map, the closed orbit d is a *stable limit cycle*.

We can also use (7) to easily calculate other properties of the system. Since Δv_{pls} is constant, v_i will approach the steady-state $v_{lc} = \frac{\beta\Delta v_{pls}}{1-\alpha\beta}$. v_{lc} can be employed to calculate the height to which the tip of the drumstick jumps during one cycle.

6. CONCLUSION

In informal tests, we found that the altered dynamics made playing single-handed drum rolls easy for both 1) directly altering the COR and 2) applying pulses with constant magnitude. The main advantage in applying pulses with constant magnitude is that drum roll limit cycles are guaranteed to be stable. However, both types of altered dynamics allow drummers to increase the drum roll rate by increasing K_{hand} or decreasing z_{h0} as in traditional drum roll playing [6]. This means that the new musical instrument is physically intuitive, which we believe should facilitate skill transfer for performers of traditional drums.

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