HAP-KIT:
A haptic interface for a virtual drum-kit

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Abstract – This report describes the design and testing of a haptic interface for a virtual drum-kit. This interface incorporates several novel features including the use of a controllable brake, force sensors and wire gearing. It is shown how these features generally improve the haptic interface and how they can be specifically used to aid simulation of a real drum. It is also shown how coherent multi-sensory feedback between the sound and haptic output can increase the realism of the haptic interface.

1. Introduction

The aim of this project is to incorporate several novel features into a haptic interface that is specifically designed to simulate a drum. There are two reasons for this; firstly to test out the novel features and secondly to test out the validity of a haptic interface for a virtual instrument.

1.1 Haptics

Haptic *adj*. 'Relating to or based on the sense of touch' [1]. Thus haptic interfaces are those that receive and transmit information through the sense of touch. To narrow this definition it is possible to define two distinct types of haptic interface, static and programmable. A static haptic interface is one that can receive and transmit information but is non-changeable. An example of this would be a normal drum, where the user can hit the drum and the drum will respond accordingly. A programmable haptic interface however allows the user to change the interfaces response. This allows active change of what the user perceives though their sense of touch. An example of this would be if the drum could be made to change instantaneously into a cymbal followed by a bucket of jelly, both of which feel very different.

The aim of this project is to enable an active haptic interface to simulate a passive interface, which in this case happens to be a drum. This will allow the interface to be used in the same way as a normal drum, whist maintaining the possibilities of an active haptic interface. To avoid confusion any reference to haptic interfaces in the main body of this report assumes an active interface.

1.2 Current haptic interfaces

The most common haptic interfaces in use today are the vibro-tactile units found in many games controllers. These are very simple devices that can vibrate with a controllable amplitude and frequency. Although simple they show the potential of haptic interfaces very well, as they can be incorporated into any computer-game and can improve the game-play greatly. Examples of their use in games include rumbling when the player has hit something, or feeling like a heartbeat that responds to the player's life-level.

A slightly more advanced interface can be found in the form of the force-feedback joy-stick. This allows force to be applied in two directions so that more realistic forces can be used. Although more sophisticated than the vibro-tactile units, these joysticks still have a very limited range in terms of area that the force can be applied.

High quality haptic interfaces are available, the most notable of these being the Phantom [2]. The Phantom is essentially a robotic arm with three degrees of freedom (d.o.f.). The user interacts with it by either placing their finger in a thimble attached to the end or by holding a stylus that is attached to the end. Both are attached by means of a universal joint. This allows forces to be transmitted to the user in three dimensions, whilst allowing the user to freely position the orientation of the thimble or stylus. Advances on this basic model have been made to include an additional three d.o.f. so that the orientation of the stylus can be controlled.

Advanced interfaces such as the ViSHaRD10 [3] hyper-redundant haptic interface are in development and offer very large workspaces. The hyper-redundancy allows the singularity to be avoided and thus makes it able to maintain high accelerations and velocities. However, these types of interface are still only being used experimentally and have not yet been made available to the public.

Although it would be possible to use the Phantom or similar to simulate a drum, they were not designed to receive or transmit the large forces or large fast movements that are inherent in a task such as drumming. This explains the necessity of designing and building an entirely new interface for this project.

1.3 Haptic musical instrument interfaces

Several haptic musical instrument interfaces have already been investigated. These include a violin (v-bow), Theremin and even an entirely new instrument.

The vBow [4] is a four degree of freedom haptic interface for a physical modelling violin synthesiser. The four degrees of freedom allow the user to feel the longitudinal, vertical, lateral and rotational forces on the bow. This haptic instrument is particularly advanced as it uses the physical synthesis model of a violin as the reference for both the sound and the forces transmitted back through the bow.

The Theremin was invented in 1920 by Léon Théremin and is an instrument that requires no physical contact to play. The performer moves their hands near two aerials, one to control the pitch and one to control the volume. However, it has been found that the addition of haptic feedback allows greater accuracy to be achieved [5].

The Cymatic [6] is a computer based musical instrument with haptic feedback. This instrument hasn't been based upon a single instrument, but incorporates elements such as plucking, hitting and bowing that are common among many instruments. Cymatic's interface consists of a force-feedback joystick and a vibro-tactile mouse. The main feature of this device is its ability to generate high quality sound in real-time that is generated by the same model that controls the haptic feedback. Unlike the vBow, the Cymatic has been used with virtual instruments that would not be conceivable in the real-world, such as sound objects with more than three dimensions.

2. Study of a real drum

To design a haptic interface for a drum it is first necessary to study the features of a real drum. The features that are especially relevant are the ones that will be limited by the haptic interface itself. The two main limiting factors in any haptic interface are the size of the workspace and the maximum speed of the user. In terms of a real drum this translates to the maximum displacement and speed of the tip of the drum-stick. As no previous research (to the knowledge of the author) has been undertaken to determine these values, it was necessary to measure them.

Firstly a video was taken of a drumming sequence, hitting a snare drum repeatedly. A measuring rule was placed next to the drum so that measurement could be made directly from the video. The next step was to play the video back one frame at a time so that the position of the stick-tip could be measured. Both the height of the stick above the drum and the horizontal distance from the centre of the drum were measured. As the frame rate of the video was known it was also possible to determine the time of each measurement in seconds. The values obtained could then be plotted to determine the maximum displacement (fig. 1, upper line). The values were then differentiated to determine the approximate speed of the drum-stick (fig. 1, lower line). The maximum displacement is approximately 0.8m and the maximum speed is approximately $0.2ms^{-1}$.

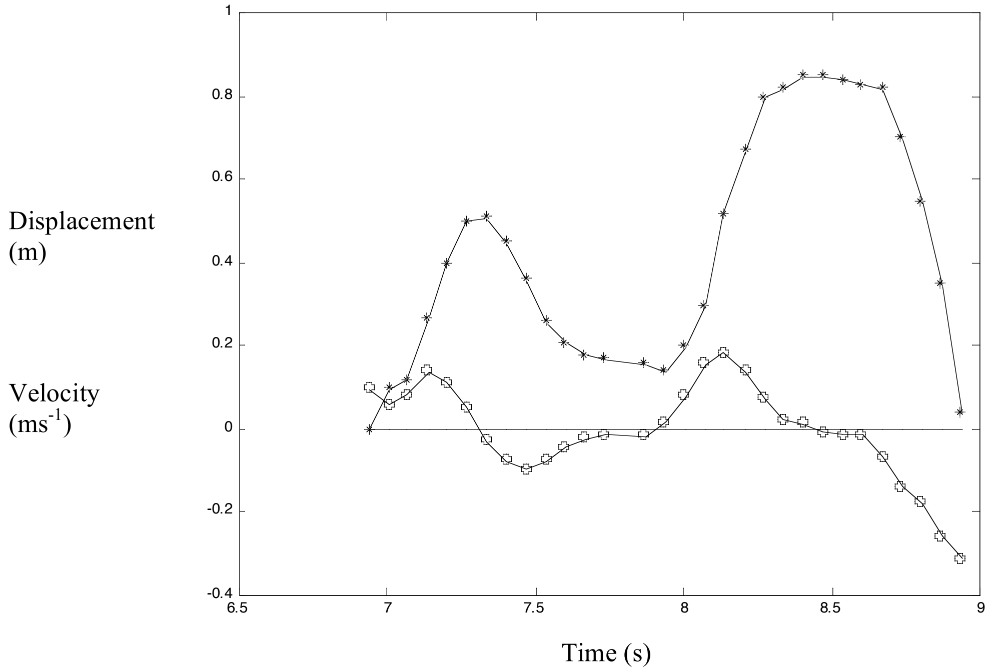


Figure 1. Displacement (top) and Velocity (bottom) of Drumstick Tip versus time (measured in m & ms^{-1}). Dashed line indicates position of drum skin (zero displacement)

3. Requirements

To design the interface it is first essential to determine the requirements of the system. Two requirements have been found in the study of a real drum; however these indicate the parameters needed to achieve a wholly realistic simulation. It is therefore necessary to find a compromise between what is possible and what will produce a near drum-like experience. Several areas of requirement are discussed below.

3.1 Reach

The size of the workspace, or reach, is the first concern as it will influence the forces and speed that can be generated. The reach is determined primarily be the number of degrees-of-freedom that are used. Three degrees-of-freedom would be ideal, as an entire three dimensional drum (or drum-kit) could be modelled. Two degrees-of-freedom would allow a ‘slice’ of a drum kit to be modelled, perhaps as a vertical plane cutting through the snare drum, tom and cymbal. However due to cost and time it was decided to limit the interface to one degree-of-freedom. This greatly simplifies the problem of workspace size, as the workspace will be determined by simply the length of the arm

The average distance covered when hitting a drum has been shown in fig. 1 to be approximately 0.8m vertically above the drum surface. However, with a one degree-of-freedom system the workspace is limited to an arc about the pivot point of the arm with a radius determined by the length of the arm. This would mean that if a height of 0.8m is to be achieved then the user would also have to move the stick 0.8m horizontally. This is obviously not simulating the real movement of a drumstick. To solve this problem it is necessary to change the type of drum hit that is intended to be performed. By making the pivot point of the arm pivot around the same point in which the stick is being held, a shorter drum stroke can be assumed where the user moves their hands without much horizontal or vertical movement, thus scribing an arc with the tip of the drum-stick.

3.2 Speed and acceleration

The maximum speed as determined in fig. 1 is approximately $0.2ms^{-1}$ although speeds well in excess of this could be generated, especially performing drum rolls. The matter of obtaining a certain speed is fairly trivial compared to the acceleration. The limit on how quickly a body can accelerate is determined by its mass, so to increase the interfaces ability to accelerate involves keeping the mass of all moving parts to a minimum

3.3 Force

The haptic interface will be transmitting force to the user through the motors, so is useful to estimate the minimum and maximum forces needed. The force will need to be considered as the force that the interface can generate at the tip of the drum-stick. The minimum force required will be equal to the average force a user can apply to the tip of the stick. However, this minimum force would allow a user who exerts more force than average to push through the virtual drum skin. Similarly, the maximum force required will be equal to the maximum force a user can apply. This would be the ideal force capacity of the interface as it would then become impossible for the user to push through the virtual drum skin. Obviously there is a limit even on this maximum force, as even a real drum-skin will tear under great force. To determine the minimum force needed, a comparison can be made with the Phantom haptic interface [2]. This can exert a maximum force of 7N. To make building a new interface worthy, it is therefore essential that the maximum force exceeds 7N.

To make the application of force both accurate and controllable, the interface may use a force sensor. Often, haptic interfaces are not equipped with force sensing capabilities and rely on positional measurements to determine the force needed. This has the inherent problem though of needing an error before a correcting force can be applied. The use of a force sensor eliminates this problem by measuring the force applied so that a controlling force can be generated without needing a positional error (although this may still occur if the motors are not powerful enough).

4. Preliminary design considerations

The design of the haptic interface has been broken down into various subsections, each addressing their relevant requirements.

4.1 Transmission

The gearing is central to the system. It will be connecting the motors, brake and arm together and will determine the nature of these components.

Firstly the type of gearing system needs to be chosen. The obvious choice is a cogged gear. These are commonly used and readily available, and are often made to fit directly to a motor. However, cogged gears are not usually made to be highly efficient or stiff. The alternative is a cable based transmission, consisting of two cylinders rigidly connected by a wire. Cable based transmissions are known to have low losses and low backlash, both qualities being desirable in a haptic interface. The use of wire gearing eliminates the inefficiencies of the friction between the teeth of cogged gears, and provides a much stiffer linkage between the motors and the arm. Wire gears can also be made to have a low inertia and yet a high power to weight ratio (the wire can transfer energy away from a large motor to a lightweight tip). The only disadvantage of using a wire gearing system is that to reap these benefits they need to be specifically made for the task.

To decide on the gear ratio it is necessary to look at the equations that determine the torque that is transmitted from the motor to the tip of the stick.

$$\text{OutputTorque}(\text{Nm}^{-1}) = \text{GearRatio} \times \text{InputTorque}(\text{Nm}^{-1}) \times \frac{1}{\text{PivotDistance}(\text{m})} \tag{1}$$

4.2 Motors

The motors will be supplying and removing energy from the system. Because high torque and relatively low speeds are required, the motors will be put behind the gearing system. The choice of motors will thus dictate the gear ratio needed to meet the required force.

4.3 Position Sensor

To control the position of the arm it is necessary to know the arms current position. To achieve this, some kind of encoder is needed to turn the position of the arm into a signal that can be input into the controller. Two methods of doing this are using a potentiometer or an optical encoder. The potentiometer method would involve the changing resistance of a rotary potentiometer being used to generate a voltage signal. The optical encoder generates voltage spikes that result from the rotation of the encoder. Software is then needed to count the spikes and produce a linear signal.

4.4 Brake

The brake is a novel addition to the usual haptic interface. The brake (or damper) is intended to assist the motors in resisting the motion of the user when at the virtual drum surface. It has been proposed that the addition of a brake would remove, or greatly reduce, the instabilities that can occur in regular haptic interfaces [7, 8, 9, 10]. There are various types of brake available including disc brakes, electro-rheological powder brakes and magneto-rheological fluid brakes. Another consideration is whether linear or rotary brakes are needed.

4.5 Base-plate

The base-plate needs to be able to support the gearing system rigidly and transmit any surplus force to the table it is resting on. This means that the plate needs to be large enough not to topple over, and also large enough to enable the use of clamps. There also needs to be enough room for electronics that need to be secured close-by.

4.6 Arm

The arm will be connected to the gears at one end and then to the drumstick at the other. To keep to requirements the arm will have to be both rigid and light. Ideally it should be simple for the arm to be removed so that different arms can be interchanged easily.

4.7 Force Sensor

A force sensor is needed near the tip of the drumstick so that the force applied by the user can be measured. A common way of measuring force is through use of strain gauges. These can be configured to measure very small strain forces, and when in a full-bridge setup, they are self correcting. It would be possible to incorporate the strain gauges directly into the arm to save weight.

4.8 Electronics

The electronics needed will include a computer with an appropriate in/out board, motor drivers, a current limiting and switching circuit for the brake and an amplifier for the force sensor. As a computer is being used for the control of the interface, the electronics linking everything together will not have to change to implement different control schemes.

5. Final Design

The final design is best described broken into the various subsystems examined above. This allows each of the subsystems to be justified and described in full.

5.1 Gearing

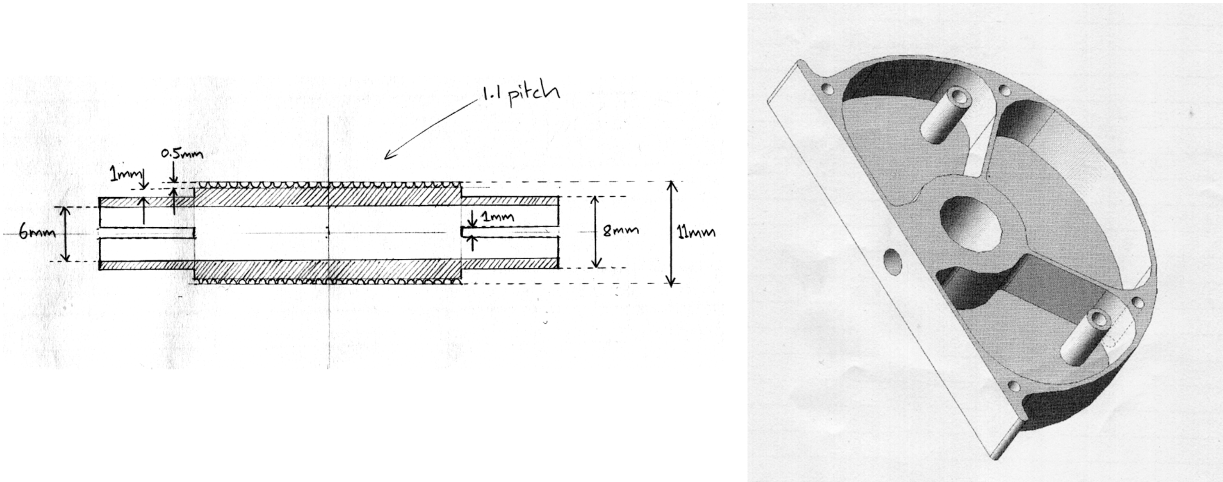
The wire gearing system was chosen to link the motors, brake and arm together. The first thing to consider is the positioning of the components. The motors definitely need to be ‘behind’ the gears; they run at high speed and need the gearing to convert the speed into torque. However, the brake could potentially positioned either behind or in-front of the gears. The trade-off involves increasing the maximum braking force, but also increasing the residual damping, or sacrificing some of the potential braking force, but keeping the residual damping to an absolute minimum. As an increased residual damping force is highly undesirable it was decided to use the brake in-front of the gears.

The next important factor to be decided is the gear ratio. This determines how much torque the motors can supply, trading off speed for torque. Using equation (1) and the values of the motor torque, pivot distance and desired output toque a suitable gear ratio can be found.

$$7.5 = \text{GearRatio} \times 0.2 \times \frac{1}{0.4}$$

$$\text{GearRatio} = \frac{7.5 \times 0.4}{0.2} = 15 \tag{2}$$

To implement this, several parts had to be designed and manufactured. The main parts needed are two cylinders for the wire to be wrapped around. As the gearing was chosen at being 15:1, one needs a diameter 15 times that of the other. To keep the size of the parts as small as possible, the smallest cylinder is designed to be only slightly larger than the motor shaft that it is attached to. This cylinder also needs a screw thread so that the wire wrapped around it does not slip. The final design of this component can be seen in fig. 2 (a). The requirements of the second cylinder include; a diameter 15 times that of the first, a way of attaching the arm, a method of attaching onto the shaft of the brake, an anchor point and tightening system for the wire and finally the need to be as light as possible. The culmination of these requirements resulted in the design of the component as seen in fig. 2 (b). To address these requirements in order: The diameter of the cylinder is 15 times the size of the first, however, it was deemed that the arm only needed to be capable of 180 degrees movement. This resulted in the flattened side and the two protrusions. The protrusions act as safety stops that prevent the arm from swinging further than approximately 200 degrees. The arm is attached by means of a screw thread in the centre of the flat side. The component is attached through a coupling to the shaft of the brake. To anchor the wire, the wire is fed through the safety stop and into the body of the component; it is then wrapped around one of the pins and back towards the flat edge. The wire is then attached to a tightening block that tensions the wire towards the flat edge. The requirement of the component to be light is fulfilled by hollowing the component out and using spokes for structural support.



(a) (b)

Figure 2. Components of the wire gearing; (a) Cross section of screw-thread coupler; (b) Pulley mechanism.

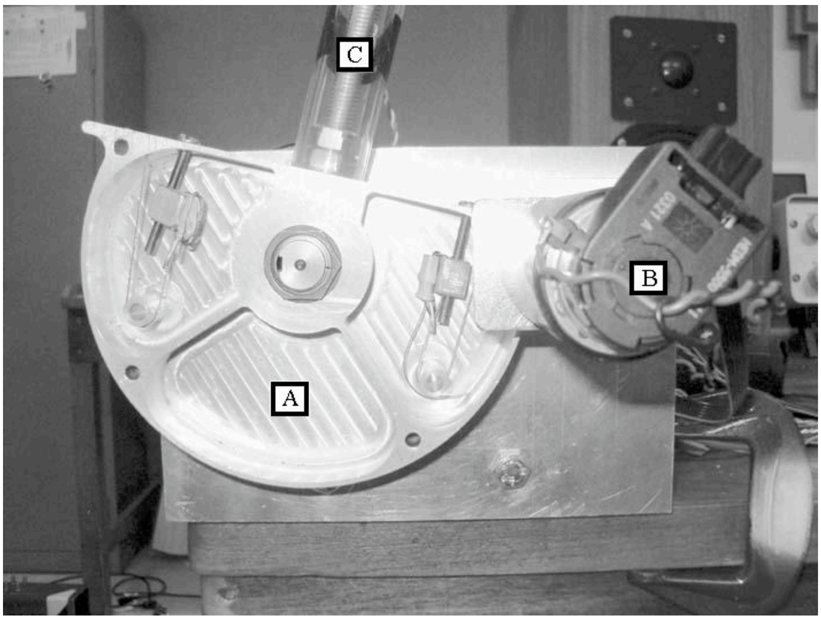


Figure 3. Assembled gear system. (A) Pulley Mechanism, (B) Motor, (C) Arm in upright position. The wire tightening mechanism can be seen inside the body of part A.

5.2 Motors

The main decision in choosing motors is the maximum torque needed. The minimum force required has already been decided upon as 7N. This then needs to be converted to torque. The length of the arm from tip to pivot is approximately half a meter, so a single motor would have to generate 3.5Nm to meet the minimum requirement. This however is through a 15:1 gear, so the requirement is reduced to 0.23 Nm for a single motor. As the gearing system allows for the simple addition of a second motor, attached to the opposite side of the screw-thread coupler, it was decided to use two motors, each capable of meeting this minimum requirement separately. This effectively allows for approximately double the minimum required force.

5.3 Encoders

The encoders are attached directly to both motors. The encoders provide a high-resolution output of the motor position and hence give an accurate measurement of the arm position. The encoder outputs are connected directly to the encoder inputs of the Multi-Q I/O board. These encoder input channels are pre-configured in the software to count the pulses from the encoder and convert them to a continuous signal. This count is started from the position of the encoders when the control scheme is run. Hence it is necessary to hold the arm in a horizontal starting position, so that the encoder output is roughly the same every time.

The encoders output a continuous signal covering a range of 31000 pulses from the arm moving from one end stop to the other. The total range of the arm from one end stop to the other is 215°. From these two figures it is possible to work out the sensitivity of the encoders in output per degree movement as shown in equation (3). Similarly the sensitivity measured in pulses per millimetre (around the radius of the circumscribed arc) can be calculated as shown in equation (4), given that the radius of the arc is 400mm.

$$\text{Sensitivity (pulses per degree)} = \frac{\text{Output over given Range (Pulses)}}{\text{Size of Range (degrees)}} = \frac{31000}{215} = 144 \tag{3}$$

$$\text{Sensitivity (pulses per mm)} = \frac{\text{Output over given Range (pulses)}}{\text{Size of Range (mm)}} = \frac{31000}{\frac{215}{360}(2 \times \pi \times 400)} = 21 \tag{4}$$

If control of the tip of the stick is going to take place whilst interacting with the virtual drum skin, it is assumed that the drum skin will only be displaced or stretched by a few millimetres, and hence will need to be controllable over those few millimetres. To be controllable, a suitable feedback signal is needed to inform the controller of the position over these few millimetres. As can be seen in equation (4), the encoders will output approximately 40 pulses over two millimetres. This shows that there is adequate sensitivity for the intended purpose.

5.4 Brake

The chosen brake to use is a Magneto-Rheological Fluid (MRF) brake. These brakes operate by magnetising a chamber of fluid saturated with iron particles. These particles form chains that exert a shear force between the housing and the rotor. When the magnetic field is removed, the chains break and only a residual damping is left. MRF brakes have many advantages over other more commonly found braking systems: They exert a high torque at low speed, require substantially less power to operate than eddy current or magnetic hysteresis brakes, operate silently, have a quick response time (under 10ms) and have a linear relationship between input current and torque generated.

There is not a great deal of choice when choosing MRF brakes. One of the major decisions that took place was whether to use a rotary or linear brake. The linear-displacement brake allows a much greater force to be exerted but severely limits the range, unless a cunning method to remedy this was thought of. The rotational brake allows easy integration with the proposed gearing system and can also be used to actually mount the gearing system. Hence the loss in maximum braking force was accepted and the rotational brake was chosen.

To use this brake it was necessary to build a current controller. This switches on a controlled 1 Amp current when 5V is applied to the input. The control of the current is important when supplying a MRF brake. If the current supplied is too high then the brake can be easily made non-functional.

5.5 Base-plate

The base-plate serves the function of supporting the gearing system and providing a stable base to be clamped to a work-bench. It was also found that due to the amount of electronic circuits that needed to be in close proximity to the motors, brake and strain gauges it was necessary to mount all of the electronics on the base-plate.

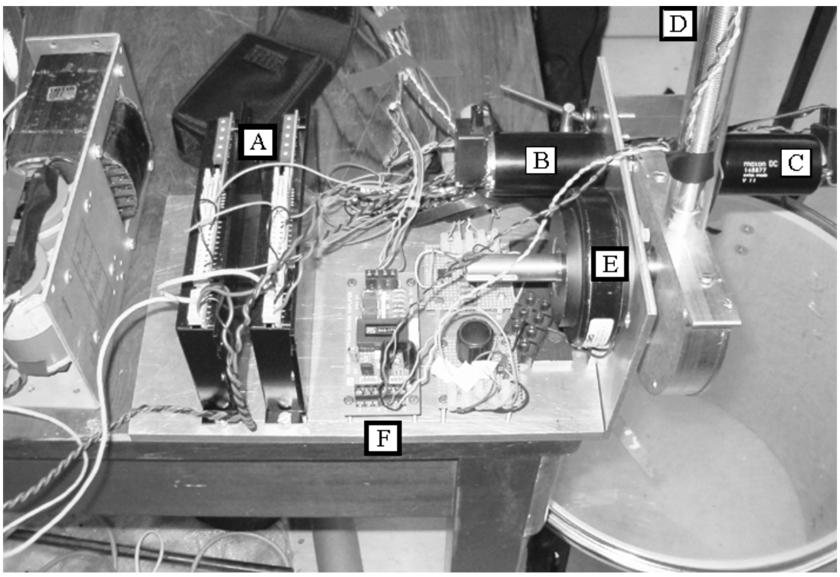


Figure 4. Baseplate. (A) Motor Drivers, (B) Motor 1, (C) Motor 2, (D) Arm, (E) Brake, (F) Strain gauge amplifier.

5.6 Arm

The arms function is to transmit force from the gearing system to the tip of the drum stick. The chosen length of the primary arm is 40 centimetres. A secondary arm is then attached at right angles to the first so that a drum stick can be positioned, via a universal joint, parallel to the primary arm. The length of 40 centimetres is chosen so that the pivot point of the arm is roughly in line with the drummer's hand. Hence if a short drum stroke is made, where the user moves only their wrist, then the arm will permit a similar arc to the user's natural movement.

To transmit forces effectively the arm needs to be strong and rigid. To achieve this, the primary arm consists of a length of metal studding acting as the core with a Perspex tube surrounding it. One end of the studding is screwed into the flat face of the gear and the proximal end terminates with the secondary arm. The Perspex tube is under compression, and the studding under tension, allowing the arm to be strong and rigid whilst maintaining lightness.

The secondary arms function is to both move the tip of the drum stick away from the end of the primary arm and also to house the strain gauges. The arm is attached at one end to the primary arm by means of a clamping system; the clamps attach onto a flattened section of the metal studding and then a nut on the studding is tightened to provide extra force (and to compress the Perspex). This method of attachment proves to be very secure and is impervious to any rotational slip that may be caused by the torque generated. The other end of the arm terminates in a universal joint that is attached parallel to the primary arm. The universal joint then holds the drum stick.

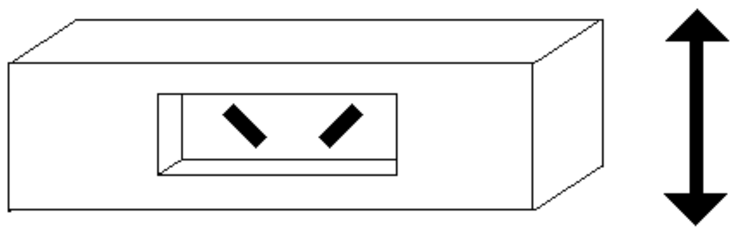


Figure 5. Strain gauge positioning. Aligned to measure force along direction indicated by arrow on the right.

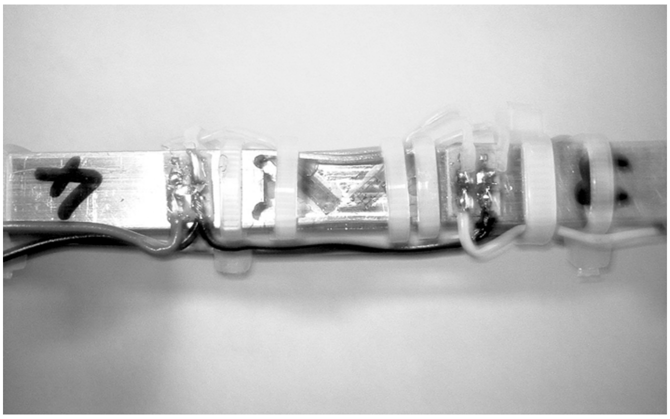


Figure 6. Strain Gauges mounted on the arm.

5.7 Force sensor

Strain gauges are used to sense the force acting upon the arm. Strain gauges were chosen because they can be easily integrated into the structure of the arm, and because they give a relatively linear output. Four separate stain gauges are used in a full bridge configuration to increase the sensitivity. This configuration is also useful as it rejects the effects of temperature, and other noise on the strain gauges. The strain gauges are mounted in a recess in the arm, and are glued into place at an angle of 45 degrees. Two are placed on either side in identical configuration. This method of mounting the strain gauges is useful as it greatly reduces the signal from axial strain and accentuates the bending strain as indicated by the arrow in fig. 5.

As the output of the strain gauges is too small to directly input to the Multi-Q I/O it is necessary to first pass the signal through an amplifier. The amplifier requires a gain of approximately 10000 to bring the signal into the 0-5 V range.

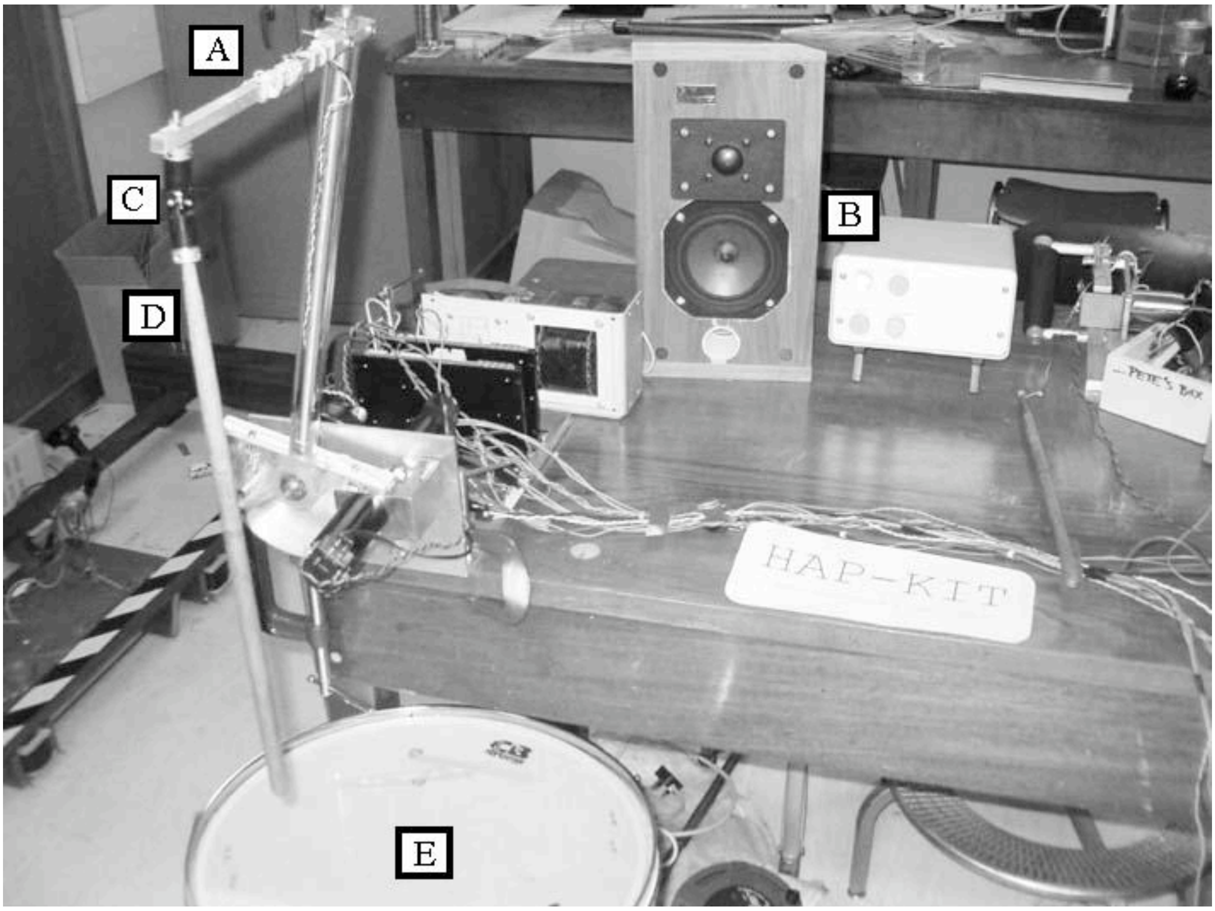


Figure 7. Entire experimental setup. (A) Position of strain gauges, (B) Speaker and amplifier, (C) Universal joint, (D) Drumstick, (E) Real Drum.

6. Control

Control of the haptic interface is an important aspect of this project. The control involves taking readings from the interfaces sensors, analysing them and then acting upon them by transmitting control signals.

To achieve this it has been decided to use the Matlab software package running Simulink with the Real-Time control toolbox. Other options would have included using other real-time control such as Xpc-target or writing a new program in C++. The Matlab option was chosen because of its compatibility with the chosen Multi-Q I/O board and its ease of use in rapid prototyping. One of the reasons why Simulink is useful for rapid prototyping is its graphical user interface which allows users to 'drag and drop' control blocks into the model. Hence the diagrams below (fig. 8-10) are images of the actual model used in testing. A second feature that increases the speed of the prototyping is that most parameters (such as the magnitude of the gain) of the blocks can be altered whilst the program is running.

The design methodology used was that of starting with a basic control scheme and improving it on an experimental basis. Progress was recorded at each stage so if something went wrong the last working example could be recalled. This was deemed the most suitable method for designing the control scheme as many of the parameters involved in the design are very difficult to work out theoretically and rely upon testing to discover. As a result of this, the control schemes below are described not only in their final state, but also in how they were developed.

The control scheme discussed below is for a simple single drum-surface with sound. The control has been split into three sub-sections, however it is to be noted that the sound control diagram (fig. 9) links up with the motor control diagram (fig. 8). The join is easily seen as the two vertical lines on the top left of fig. 8 join with the two vertical lines on the bottom left of fig. 10.

6.1 Motor control

The motor control is the central part of the haptic interface as the motors are the sole means of inputting energy into the system. The function of the control is to acquire a signal from the sensor outputs, process this signal and then output the processed signal to the motor drivers.

The simplest control scheme for a haptic device consists of a negative feedback loop containing a non-linearity. This creates an area of 'free-space' and an area that acts like a spring from the tip of the stick to the boundary with free-space.

To refine this, it is then possible to include a gain in the feedback pack (on either side of the non-linearity). This then allows control of the spring constant so that the stiffness of the spring can be increased. For added control a Proportional-Integral-Derivative (PID) controller can be used to allow the inclusion of both integral and derivative terms. These act like inertia and damping respectively. This can be seen as the middle feedback loop in fig. 8.

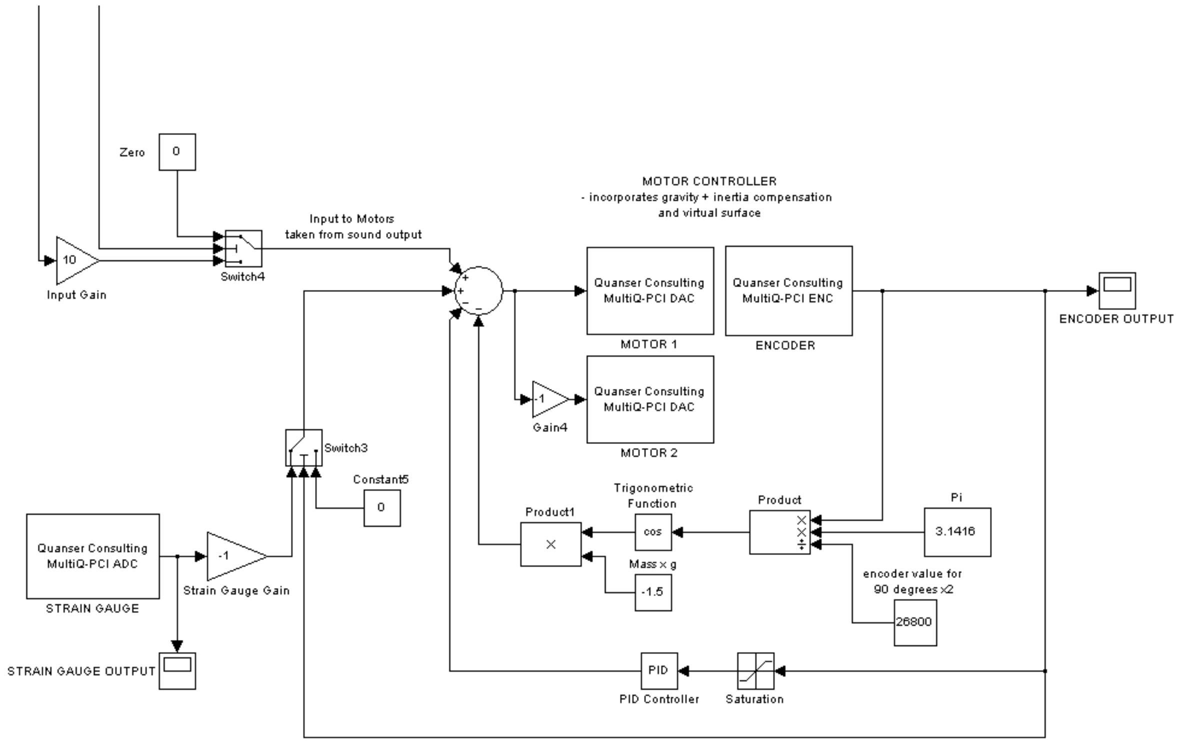


Figure 8. Simulink diagram of motor Control.

Gravity compensation can be added, so as to remove some of the weight of the arm and gears. The principle behind this is that if the mass of the arm is known along with the acceleration of gravity, the downwards force of the arm can be found. As the arm works in a circular arc then the vertical component of this force can be found and then compensated for. In practice this works out to involve converting the encoder output between horizontal and vertical positions to a scalar value between zero and Pi. The cosine of this value can then be found to give the vertical component. This figure is then multiplied by a suitable gain so as to repel this downwards force. This is implemented in the innermost feedback loop as shown in fig. 8.

Although gravity is compensated for, the inertia of the arm is not. This means that the user still has to supply the energy for accelerating (or decelerating) the arm. One solution to this is to use the force sensor on the arm to detect the force applied by the user. The motors can then be used to assist the user in accelerating or decelerating the arm. To implement this in the control model it is first necessary to include a switch to turn the inertia assist off when at the drum surface. If it was left on, it would have the undesirable side-effect of assisting the user in pushing through the virtual drum surface. When the tip is above the virtual surface, the control action used is simply the output of the force sensor multiplied by a suitable gain. This signal is then simply summed with the feedback loops to obtain the signal to be passed to the motor.

Finally, the last part of the motor control to be implemented is the addition of the drum skin vibration. This involves taking the sound generated and generating a corresponding vibration on the virtual surface. It is therefore necessary to take the output of the sound generator and the encoder output (so as not to confuse the motor control diagram) from the sound controller. These can be found on the top left of the motor control diagram in fig. 8. A switch is used so that the vibrations are only turned on when in close proximity of the drum skin (within approximately a millimetre). To generate the motor control action the output of the sound generator is used. The sound signal is put through a thresh-holding block that only lets the positive part of the signal through (as seen in figure 10). This stops any motor force being generated that acts towards the drum skin and not away from it. This signal is then multiplied by a suitable gain before being passed through the aforementioned switch and into the motor control summing junction.

6.2 Brake Control

Although seemingly simple the control for the brake took longer to develop than anticipated. This in part arose from the fact that the inclusion of such a brake in a large haptic interface had not been made before. However, magneto-rheological fluid brakes have been used in smaller haptic applications. [11]

The initial idea for a control scheme was to simply turn the brake on when the tip of the stick was at, or beyond, the position of the virtual surface. This scheme had the flaw however of ‘sticking’ inside the virtual drum and indeed also on the surface. This occurred because the control did not distinguish between when the user was moving the stick in a downwards or upwards direction.

The improvement on this basic scheme came by calculating the differential of the encoder output, so as to determine the direction the tip of the stick was travelling in. The mathematical formula of determining the approximate differential is given in (5). Where $V_{estimate}$ is the velocity estimate, V_{old} is the previous velocity estimate, x_n is the current encoder postition and x_{n-1} is the previous encoder position.

$$V_{estimate} = 0.2 \times V_{old} + 0.8(x_n - x_{n-1}) \tag{5}$$

Although this system works relatively well and removes the problem of 'stickiness', the control still relies on the movement of the arm to generate a control action. This means that the tip of the stick will always pass through the drum skin before the brake is activated. To resolve this problem it was decided to use the output of the force sensor in conjunction with the previous scheme to sense in which direction the user is applying a force and hence activate the brake without the arm having to move. The implementation of this can be seen in the lower half of fig. 9. When these two schemes were run together it was found that the differential term found using the method described above had too much high frequency noise. Hence a transfer function that estimates the differential, but also contains a low-pass filter term was used instead.

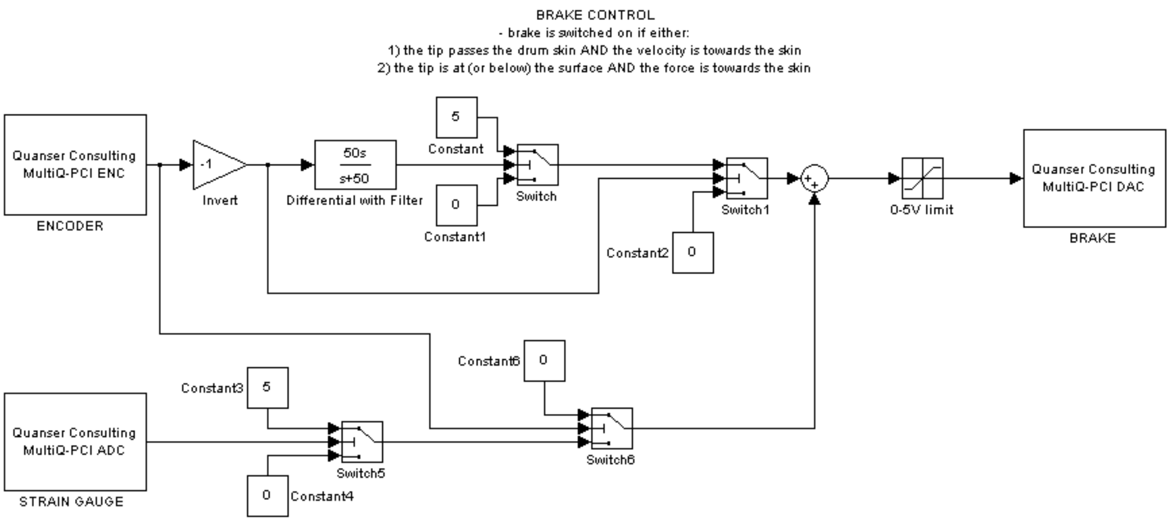


Figure 9. Brake Control.

6.3 Sound

The most important aspect of a drum-kit is obviously the sound that it produces. That is why even though this project focuses on haptics it is still necessary to include sound feedback. There are many different methods in which sound feedback could be achieved. The simplest would involve triggering a pre-recorded sample every time the drum is struck. This would allow the user to know when they have struck the drum, but not anything else. An improvement on this would be to alter the amplitude of the sample in response to how hard the drum is struck. This still has the problem though of using a single unchanging sample to represent all the possible timbres and sounds possible when playing a real drum.

A solution to this problem is to generate the sounds in real-time. This is entirely possible, albeit in a rather crude form, using Simulink. To generate a simple drum sound a sinusoidal waveform is modulated in amplitude so that when the drum is struck the amplitude rises to a level relational to the speed of the strike. This level is then decreased over a relatively short amount of time to add 'decay' to the drum sound.

A major advantage of using this method is then made apparent. By generating the waveforms inside Simulink it is then possible to not only feed the audio back to the user, but it is possible to also feed the tactile information back to the user through the motors. This adds the very important aspect of sensory coherence. If both the ears and hands are experiencing the same vibration then the virtual drum will instantly become much more realistic.

To enhance this effect it was decided to not use only one sound generator, but two running in parallel, with the second outputting a wave at half the frequency of the first. Although the lower frequency wave is less audible than the first it provides stronger tactile response. The coherence between the audio and tactile is not lost as the second wave is simply a harmonic of the first.

The final sound generator, including the second waveform, is shown in figure 10. A differential term, switch and a memory block are used to generate an impulse in response to the speed of the stick as it hits the surface. This signal is then split in two to generate a signal with decay (It was found effective to increase the delay time for the lower sound). This magnitude term is then multiplied with the desired sinusoidal waveform. Finally the two signals are summed and fed to both the speaker output and down to the motor control.

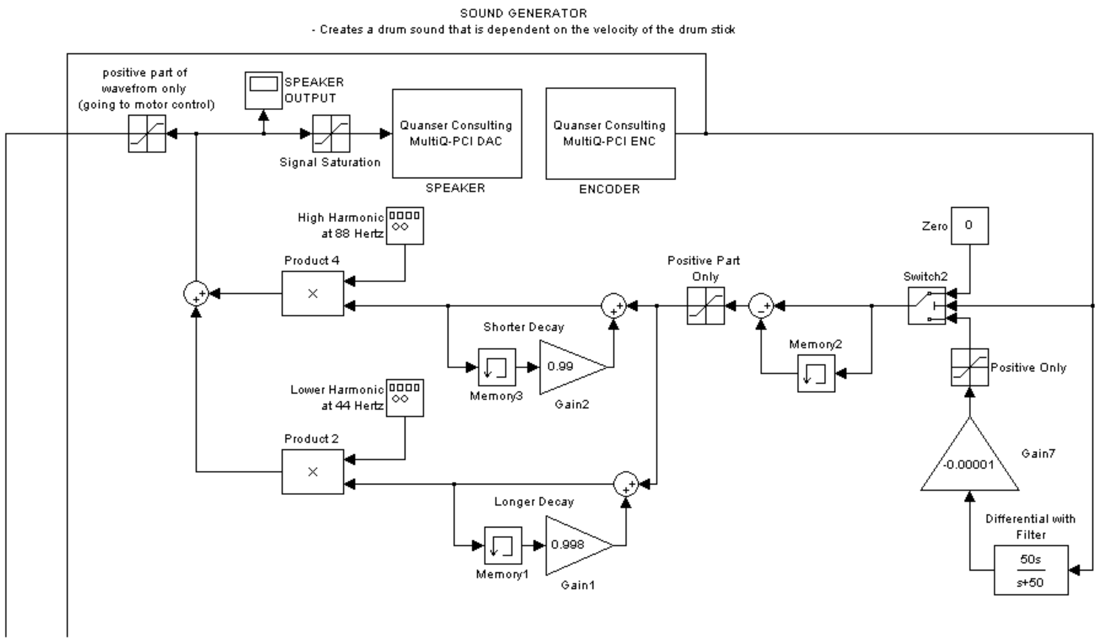
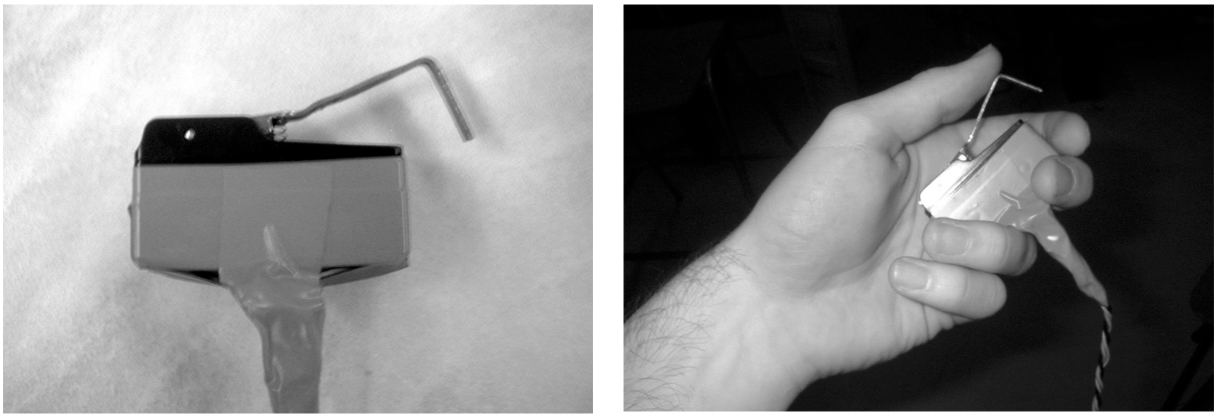


Figure 10. Sound Control.

6.4 Addition of a switch

Whilst designing the control schemes described above, it was found that a simple method of switching between two control schemes quickly would be greatly beneficial. For this purpose a hand-held switch was made to plug directly into the computers I/O board. The switch was found to be very useful in three areas; firstly it could be used as a 'dead-man' switch that would cut the motor supply if the switch was released, secondly as a means of comparing two control schemes quickly, and thirdly (and most importantly) as a performance control that allows the user to switch between two types of virtual drum whilst playing.



(a) (b)

Figure 11. (a) Hand-held switch; (b) switch in use.

The switch has been used to implement five different control schemes. The first uses the switch to turn on the gravity and inertia compensation, which is used in determining the effectiveness of the gravity and inertia compensation control. The second turns on the standard drum, used in demonstrating the interface with and without the virtual drum. The third changes the sound of the drum whilst maintaining the same haptic feedback. The fourth switches between two drums, the second drum being higher in both position and pitch than the first. The fifth turns the virtual drum upside down, so that the user strikes the surface from below. The upside-down drum is made to emit a different tone to the first. See Appendix 11.4 for an example of the "turn-drum-upside-down" control scheme.

7. Results

The results have been sub-divided into sections that progress from calibrating and testing individual parts and parameters, through to a comparative study with a real drum.

7.1 Strain gauge calibration

So that the output of the strain gauges can be related to the actual force that is applied to the tip of the stick it is necessary to calibrate the strain gauges. This involves applying a range of forces on the tip of the stick and measuring the corresponding voltage output. Full results are in appendix 11.2.

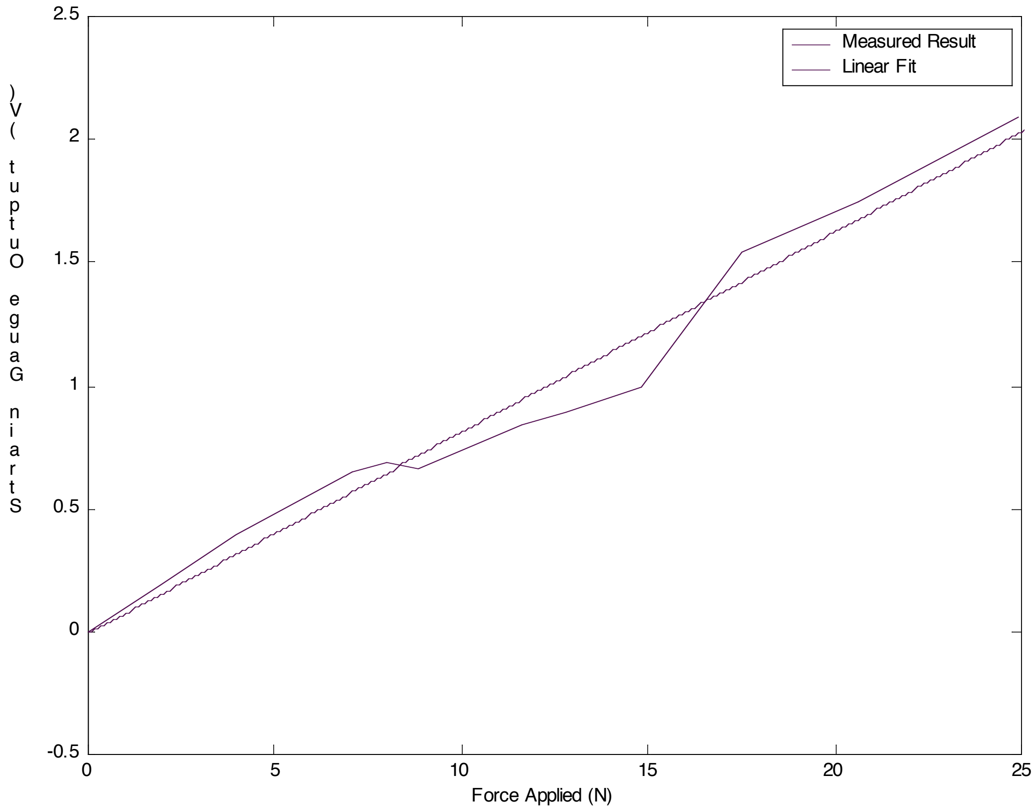


Figure 12. Graph of strain gauge input versus output.

7.2 Force

The measurement of the force can be made by use of a force meter, with the option of checking this reading against the strain gauge output. So as not to obtain a spurious result, the force was measured multiple times and the mean was taken. Each motor was measured separately, then both motors together and then the brake. To check that the forces add up, the force was then measured with both motors and the brake on. The results of this are shown in the table below.

Table 1. Measurement of force

Component	Theoretical Force (N)	Actual Force (N)
Motor 1	7.5	1.9
Motor 2	7.5	2.5
Both Motors	15.0	5.8
Brake	5.0	4.6
Motor 1, Motor 2 and Brake	20.0	14.8

This shows that the output of the motors is a lot less than they should theoretically output. The brake however is only slightly under the theoretical value. A discontinuity can be seen in the output of both motors and the brake at the same time compared with what it should be from summing the motors and brake separately.

7.3 Position

The position of the tip of the stick can be found by measuring the output of the encoders. As the encoder output is in encoder pulses, the reading need to be converted to metres. This then gives the position output in metres measured around the radius of the arc. The position graph is useful as it shows how far into the virtual drum-skin the drum stick passes. This is one of the main tests of a haptic interface, and is one of the main reasons for using a brake. Comparison can be made between figures 13&14 to see that when the brake is used the stick, on average, does not penetrate as far into the virtual drum-skin. As a further test, the position graph in fig. 14 can be compared to the position curve in fig. 1 and it is found to be very similar.

The position graph can also be used to show that there are no instabilities or oscillations when the tip of the stick is in contact with the drum skin. These would appear around the zero point in the form of higher frequency oscillations.

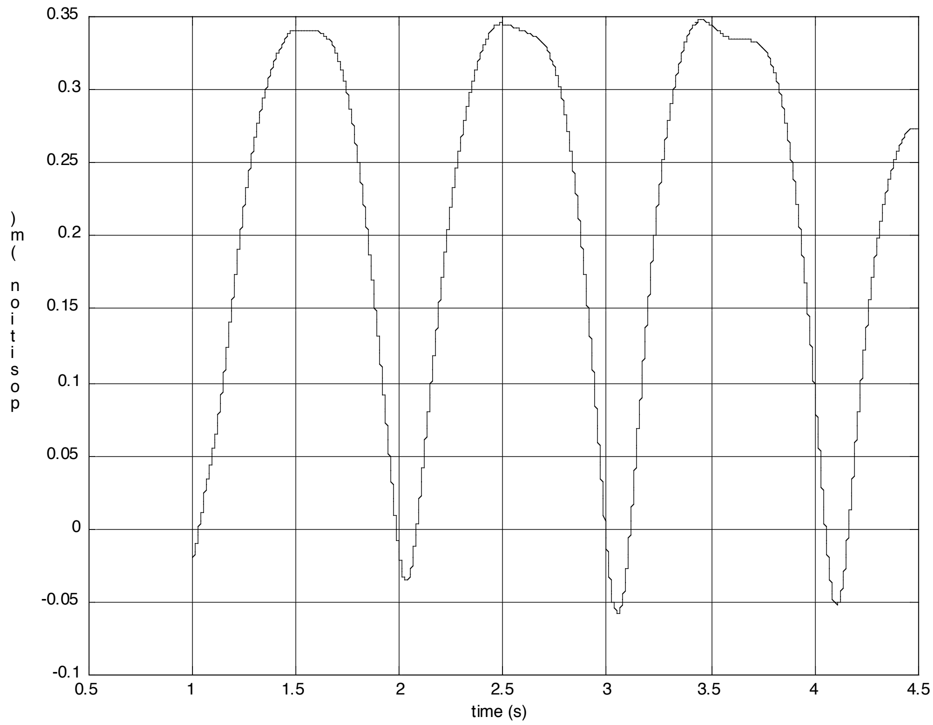


Figure 13. Postion vs time for virtual drum without brake. Drum-Surface lies on the zero line.

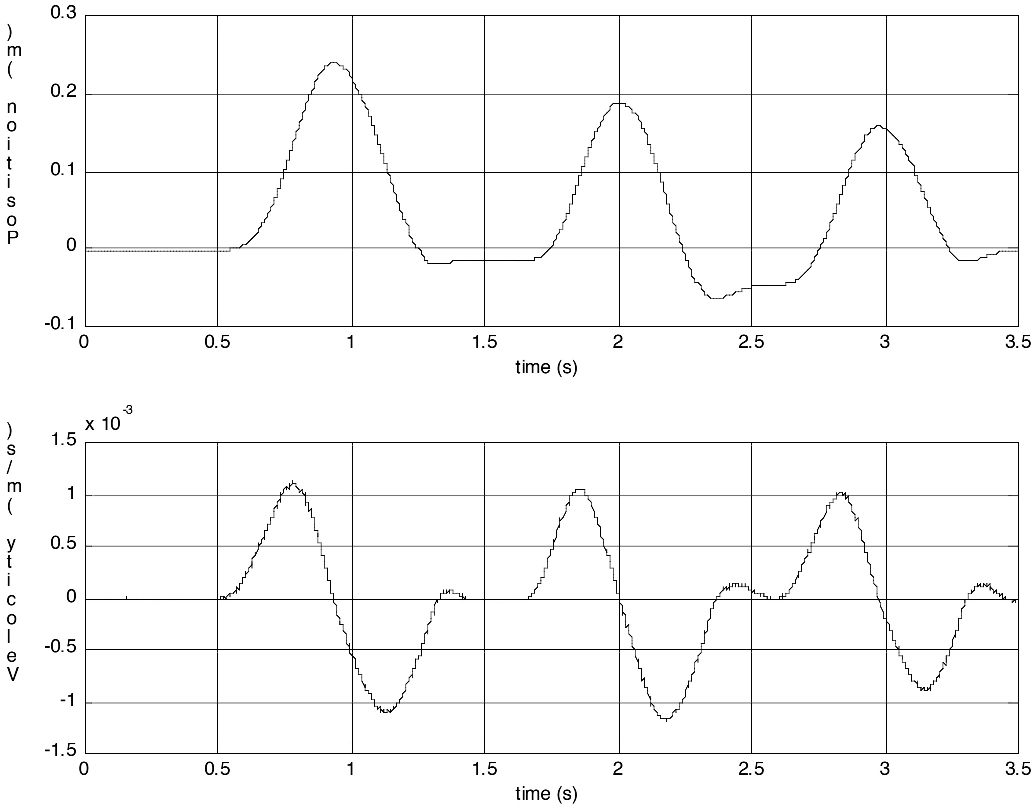


Figure 14. Position and Velocity graphs of the tip of the drum stick as it impacts the virtual surface. (With brake on)

7.4 Velocity

The velocity of the tip of the drum-stick can be found by differentiating its position as shown in fig. 14. This graph can be compared to the velocity curve found in fig. 1 that was generated by a real drum, and it is found that the values are quite similar. The velocity graph can also be used to determine the maximum speed reached by the tip of the drum-stick.

7.5 Questionnaire & testing

To gain insight into how the virtual surface compared with the real drum surface, the subjective opinion of several people was needed. This also gives the opportunity to record the output of the encoders and strain gauge, so that a fair average of their outputs can be made.

The two main questions that need to be addressed are; 'how does the virtual surface compare with the real surface' and 'what effect does the brake have'. To answer these, a short testing session and accompanying questionnaire were devised (as shown in appendix 11.3). The tester is first asked to play along to a rhythm on the real drum. This is then compared to playing a rhythm on the fully working virtual drum, and the user compares the two. The brake is then switched off and the tester is asked to play the same rhythm on the virtual drum (this time with no brake and only motors). The comparison is then made between the virtual drum with and without the brake.

Table 2. Questionnaire Results. The total number of ticks made in each box is given with a percentage value underneath. Boxes that contain n/a were not given as a choice for that question.

Question	Real Drum	Surface-A (with brake)	Surface-B (without brake)	Not Sure
1) Which surface was firmer?	12 (86%)	0 (0%)	n/a	2 (14%)
2) Which had more bounce?	4 (29%)	10 (71%)	n/a	0 (0%)
3) Which was easier to keep time?	10 (71%)	2 (14.5%)	n/a	2 (14.5%)
4) Which surface was firmer?	n/a	8 (57%)	3 (21.5%)	3 (21.5%)
5) Which had more bounce?	n/a	0 (0%)	12 (86%)	2 (14%)
6) Which was easier to keep time?	n/a	4 (29%)	9 (64%)	1 (7%)
7) Which is most like the real drum?	n/a	7 (50%)	7 (50%)	0 (0%)

Fourteen questionnaires were completed, giving sufficient results to make the questionnaire relevant. The first three questions regard the comparison of the real drum and surface-A (the virtual drum with the brake switched on). The results of question one show that the real drum surface is definitely firmer than surface-A, however there is some indecision present with 14% choosing the 'not sure' option. Question two has a majority deciding that surface-A has more bounce than the real drum. This is a surprise, as surface-A has the brake switched on, and thus damps the re-bound of the stick. Question three gives the result of the real drum being easier to keep time with. This most probably had a large influence from the restriction of the movement of the stick. Limiting the movement to an arc resulted in people pushing against the possible movement and hindering their ability to keep time.

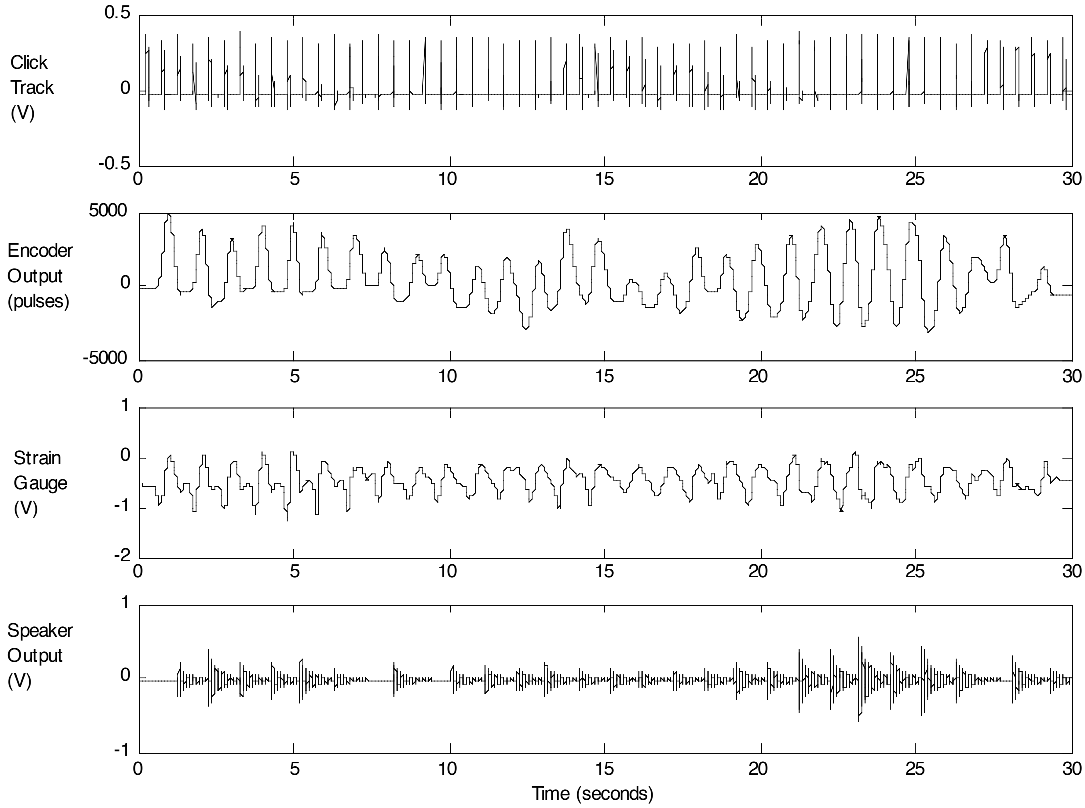


Figure 14. Example of data recorded during questionnaire. This is using surface-A (with the brake on)

Questions four, five and six are comparing surface-A (brake on) with surface-B (brake off). Question four proves that, as expected, the addition of the brake makes the surface appear firmer. Similarly, question five shows that when the brake is switched off, the surface is more bouncy, due to the lack of damping. What was unexpected however was that the bouncier surface proved to be easier to keep time with (question six).

Question seven, 'Which is most like the real drum' provides a rather interesting result. A completely even amount of people chose each type of surface as the closest to a real drum. From this result emerges an interesting idea. It could be possible that rather than both methods being equally unlike the real drum, both methods could contain elements that are like a real drum, and that if these are found it would be possible to simulate a real drum more accurately.

7.6 Integration with a real drum-kit

Although the ultimate test for a virtual drum is to compare it directly with a real drum, a slightly subtler test is how well the virtual drum integrates with a real drum kit. This has been tested and it has been found that the Hap-Kit fares much better in this test than in a direct comparison. The reason for this is that in a direct comparison the user uses the same technique for both the real and virtual drum (which they should do to maintain scientific procedure). In comparison, when both real and virtual drums are used at the same time it has been found that the user quickly adapts to use the virtual drum in any way that improves their ability to play a rhythm

It is when the user starts to adapt their technique to maximise the performance of the virtual drum that interesting and unforeseen techniques emerge. An example of this is how instantaneously turning the drum upside down can actually be used to perform some rapid drum rolls. If the user is above the virtual drum-skin when the switch is depressed, the drum stick is suddenly 'inside' the virtual drum and is propelled outwards. By successive switching the drum stick can be made to rapidly move back and forth across the skin, each time triggering a drum hit.

8. Further work

A major improvement would involve using physical modelling synthesis to model the drum [12]. As the model dictates the output of both the sound and force, a better model would instantly improve the system. A proposed method of achieving this is through the use of the C++ synthesis toolkit [13]. The synthesis toolkit provides a wide range of tools to fabricate physical modelling synthesisers that could be used to create a realistic model. An alternate method has been described in [12] that involves using a finite element method of calculating the vibrations in a virtual object. This method remains largely impractical though, as it requires a lot of computing power to process a full finite element model.

Another method of creating an advanced model would be to create an appropriate transfer function for the position of the drum skin. The advantage of this method is that it could be easily incorporated into Simulink and the current model. However, although it would be relatively easy to create a simple model (a simple under-damped system would work) it would be much harder to create a complex model unless techniques such as system identification are used.

To increase the maximum torque of the motors it would be possible to deliberately supply them with more current than the stated maximum. To lower the risk of damaging the motors it would be necessary to water cool them. As the motors are stationary, it would be a relatively simple task to fit copper tubing around the motors so that water could be pumped around them.

It has been proven [14] that Passive Impedance Modulation allows human drummers (and robots) to precisely control the frequency of drum rolls that are too fast to perform directly through muscle control. It would be an interesting to see if Passive Impedance Modulation could be used in a similar way when used in a haptic interface. This may allow the haptic interface to transmit frequencies that are beyond the controllers speed. Frequencies this high would be particularly suitable for tuned virtual instruments as the user would benefit from feeling the frequency of the note being played.

9. Conclusion

It has been shown that the addition of a controllable brake to a haptic interface can increase the firmness of the virtual surface, but it has not been proven that this is a desirable result in the application of a virtual drum. However, the inclusion of the brake does help prevent instabilities when the user is in contact with the surface, and if thorough control schemes are researched, then controllable brakes would become very useful in many haptic interfaces.

It has also been shown that including coherent multi-sensory feedback, such as the haptic feedback of the sound, greatly increases the realism and believability of the haptic interface. This is certainly a research area that deserves further consideration.

Finally it has been proven both that haptic music-instrument interfaces can be used inter-changeably with traditional instruments, and that they provide a very good focus for haptic research. Reasons for the second point include; the specific challenges that particular instruments create, the ease in which people can intuitively test and use them, and most importantly the interest that they bring to haptics research.

Acknowledgements: William Harwin, Peter Tolsten, Mike Hilton and everyone who helped in testing.

10. References

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Web addresses are correct as of 1st April 2004

11. Appendices

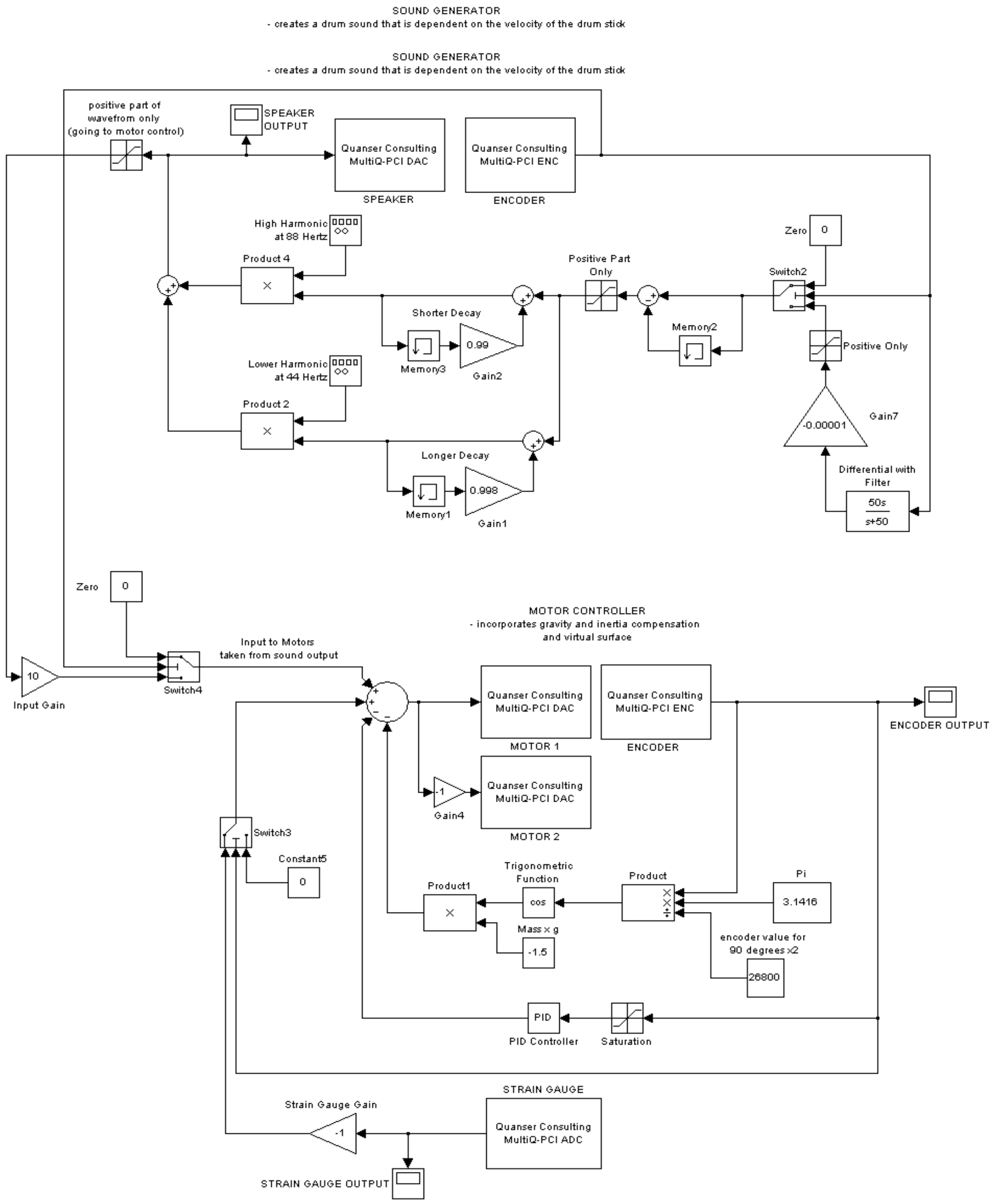
11.1 Components

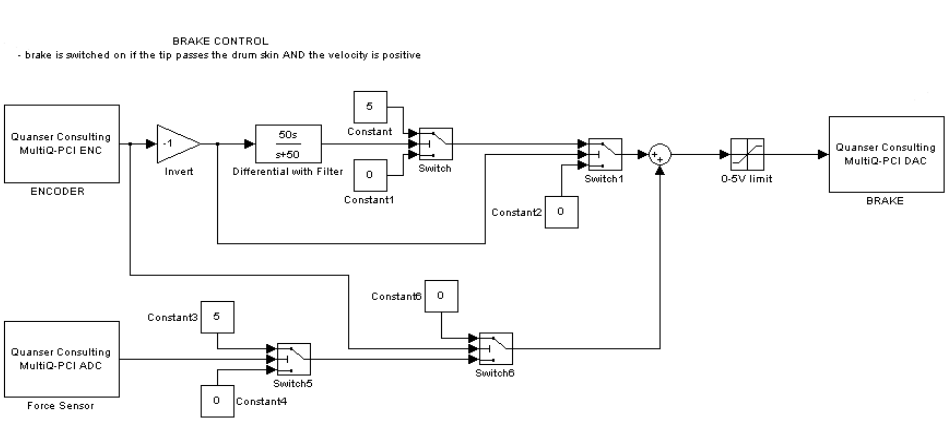
Component	Details	
MR Brake	Description	Controllable Brake
	Manufacturer	Lord Rhoenetic
	Serial Number	MRB-2107-3
	Maximum On-State Torque	5.6Nm
	Minimum Off-State Torque	<0.3Nm
	Maximum Current	1 Amp
	Resistance	8 Ohms
DC motor	Description	Graphite brushed DC motor.
	Manufacturer	Maxon
	Serial Number	RE40 – 148877
	Maximum Continuous Torque	201 mNm
	Maximum Continuous current	3.33 Amps
	Nominal Voltage	48 V
Motor Driver	Description	ServoAmplifier to drive motors
	Manufacturer	Maxon
	Serial Number	ADS 50/10 – 201583
	Supply Voltage	12-50 VDC
	Maximum output current	20 Amps
	Continuous output current	10 Amps
Encoder	Description	3-Channel encoder to fit DC motor.
	Manufacturer	Maxon
	Serial Number	110514-HEDL

11.2 Strain gauge calibration

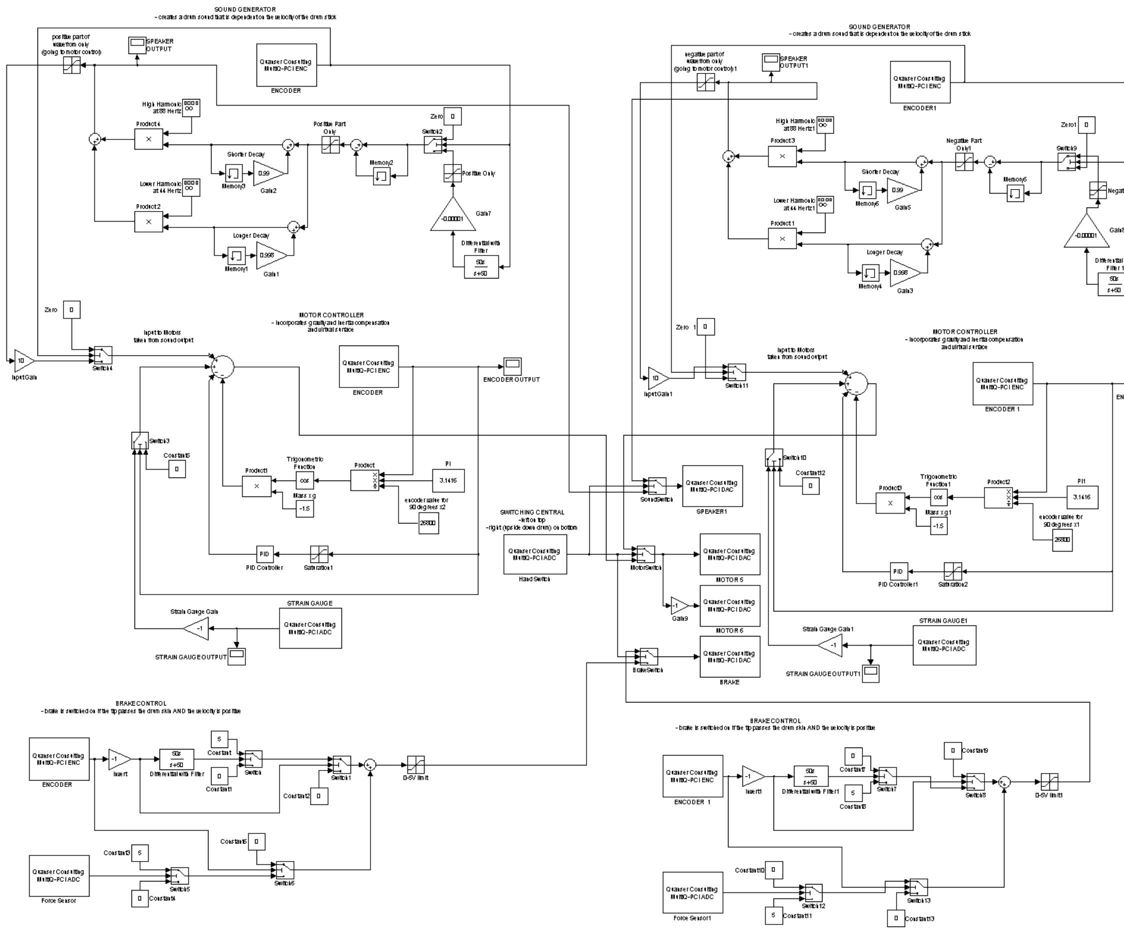
Actual Force Applied (N)	**Output of strain gauges (V)**
0.00	0.00
1.96	0.20
3.97	0.40
7.06	0.65
7.95	0.70
8.80	0.67
11.6	0.85
12.7	0.90
14.7	1.00
17.46	1.55
20.59	1.75
24.89	2.10

11.3 Standard Control Diagram

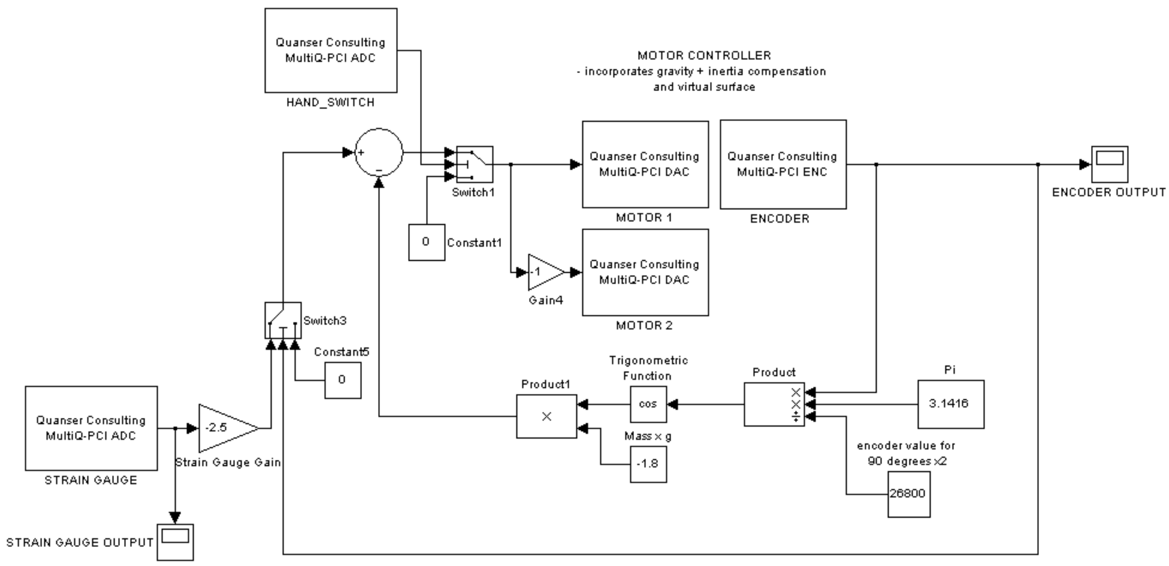




11.4 "Turn-drum-upside-down" Control Diagram



11.5 "Turn-on-Gravity" Control Diagram



11.6 Questionnaire

HAP-KIT

QUESTIONNAIRE

Name:

Procedure:

- 30 seconds playing real drum in time with click
- 30 seconds playing Hap-Kit surface-A in time with click
- 30 seconds playing Hap-Kit surface-B in time with click

	Real Drum	Surface-A	Not Sure
1) Which surface was firmer?	☐	☐	☐
2) Which had more bounce?	☐	☐	☐
3) Which was easier to keep time?	☐	☐	☐

	Surface-A	Surface-B	Not Sure
4) Which surface was firmer?	☐	☐	☐
5) Which had more bounce?	☐	☐	☐
6) Which was easier to keep time?	☐	☐	☐

	Surface-A	Surface-B
7) Which was most like the real Drum? (Please give a reason underneath...)	☐	☐