Marching onwards

Procedural synthetic footsteps for video games and animation.

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ABSTRACT

Puredata is used to demonstrate a flexible and efficient approach to one problem in procedural game audio, that of creating footsteps. A model of ground pressure curves from bipedal movement combined with a synthesis layer and mapping of force to frictional excitement emulates the movement of actors on a surface. The speed and weight of the actor, the material composition of the ground and the work/speed ratio (approximated by ground incline) can be dynamically modified. Efficiency for real-time clientside execution is a goal, such that the code may be embedded into world objects.

Keywords

Sound Design, Footsteps, Synthesis, Puredata, Procedural Audio, Biomechanics, Bipedal Motion, Computer Games, Computer Animation

1. INTRODUCTION

Footstep sound effects are an integral part of video games and computer animations. Their function is both to signify the approach of an unseen actor and to highlight movements of the player character. Footsteps make an interesting study because they are well understood from an aesthetic standpoint with a rich history in film and game sound literature, and they are sufficiently complex as multi-variable dynamic events to demonstrate the effectiveness of a procedural synthetic approach. A typical set of sampled footsteps contains examples for many discrete velocities, character footware and surface materials. Permutations of these variables may require tens of megabytes of digitised data and an elaborate selection matrix to affect runtime playback. The solution given replaces this large data set with just a few kilobytes of code which can effectively create a large set of sound effects. Not only does this offer enormous space efficiencies it allows for continuous dynamic control of weight, actor speed and surface material makeup. This is something unobtainable with sampled data however large the set of recordings.

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2. AIMS

The aim is to demonstrate a synthetic solution based on a model of plantar pressure during bipedal locomotion. Beginning with a study of biomechanical research revealing the ground reaction force (GRF) of a human foot during walking, creeping and running a curve approximating pressure is generated. The generator must be efficient and capable of producing time scaled control signals corresponding to expected pressure for different modes of movement. By applying this as input to a synthesiser which mimics the sound produced by particle compression and material deformation the aim is to create a range of realistic footstep sound effects. As a secondary objective, the effectiveness of Puredata as a tool for rapid prototyping and development of audio synthesis code for games and animation will be demonstrated.

3. ANALYSIS

For bipedal movement patterns of force are observed which vary in three ways. Variation occurs for each step, for the phase relation between steps, and along a discontinuous range from creeping to running as different muscles and rhythms are used. Within each step the contact of the foot approximates a circular segment or that of a wheel of radius approximately 30 percent of the leg length [4]. Three distinct features can be identified during a single step, heel strike, roll and push off. The heel strike occurs on the leading foot and represents zero or negative work depending on whether the actor is running or walking. It is during this part of the step that maximum power transfer occurs and where the absolute value and rate of change of force is greatest. During the second stage weight is transferred from the heel to the ball in a "C" or "S" shaped curve rolling from heel, along the outstep of the foot and crossing the metatarsals to end just before the big toe. It seems that this movement maximises the contact distance and effective size of the foot. The last part of the step where the ball of the foot is used represents the greatest part of the positive work phase as the actor pushes body weight forwards. The GRF of a single step (from Adamczyk, Collins and Kuo [4]) is shown in `Fig.1`

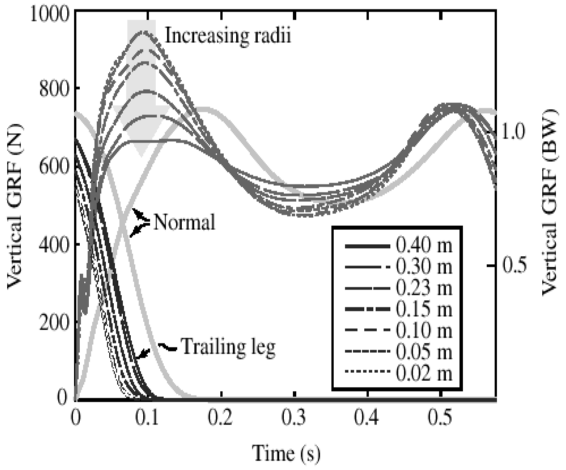

Figure 1: GRF Human step

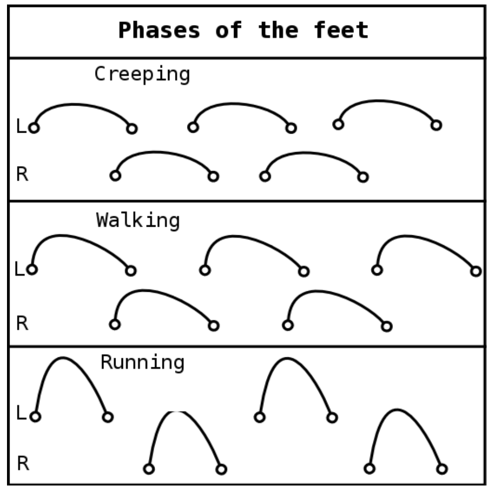

Figure 2: Left-Right phase for different movement speeds.

3.1 Phases

The bipedal duty cycle and overlap varies considerably according to velocity. The overlap, or phase, is increased for slower walking speeds and decreases towards running speed. The use of the phrase "break into a run"suggest some degree of discontinuity between walking and running modes. This seems best dealt with by applying an intervening non-linear function to the actor velocity variable to set the desired inflexions. While the pattern of ground reaction force is largely the same for each step, though compressed or dilated with changing actor velocity, the phase of steps and the vector of forces corresponding to useful locomotive work changes between slow and fast movement. While accelerating, the actor body must do more work which increases the force found in the push-off phase when the ball is in contact. When slowing down force is shifted to the heel impact where negative work is done. Phase and amplitude variations considered below for three modes of movement, each of which produces a distinctive pattern strongly suggestive of that human movement mode when applied to a suitable synthesis unit.

3.2 Creeping

The creeping cycle (`Fig.2a`) is most obviously found in predators where evolutionary advantage is obtained by minimising sound during movement. Since sound output can be approximated by rate of change of pressure the predator obtains stealth by an even application of pressure, corresponding to dominance of the roll phase in hominids. This mode is characterised by an increased overlap of plantar contact so that weight is distributed carefully over both limbs.

3.3 Walking

Walking may be characterised as a compromise of effective locomotion, minimisation of stress and metabolic cost. The phase overlap varies between about 10 percent and 20 percent of duty cycle (`Fig.2b`). [4] When walking, the kinetic energy given by the velocity of the body mass and the sum of kinetic and potential energy due to raising the body mass have opposite phase. Kinetic and potential energy are exchanged in a pendular mechanism such that muscular work and movement of the center of mass reduced. [3]

3.4 Running

Running (`Fig.2c`) can be considered a maximisation of locomotion [2] In running, kinetic energy of the body mass and potential energy are in phase, which suggests a bouncing mechanism. [3] The transition between heel contact and ball push-off is significantly reduced and the phase overlap and heel phase amplitude tend to zero. In this mode the actor has at most one foot in contact with the ground at any time and for fast movement can be completely airborn.

4. METHOD

First we obtain an acceptable approximation of the GRF signal. The experimental setup consisted of Puredata, Octave and Gnuplot, some recordings of footsteps and Audacity for spectrum plots. From example recordings, plots of mean amplitude were taken in frequency bands appropriate to a small set of materials, namely grass, snow, gravel, wood, metal and dirt. Each of these identifies features appropriate to a change in the GRF signal. Features of real sounds correlate nicely to the the measured force values of `Fig.1` Because there are two feet which must overlap in phase the Puredata program shown is an abstraction for one foot, in synthesis a pair of these are used. The synthesis settings discussed are for gravel, which makes an effective demonstration being typical of the friction-excitation behaviour of many materials.

4.1 Control signal by superposition of cosines

The first attempt to approximate the observed data efficiently used three half cycles of a cosine, time shifted and mixed to create a three stage envelope. By splitting a unit cycle into three segments of $\pi/3$ using `[clip~]`, re-seating at zero and then normalising each before taking the cosine a 3 hump curve is obtained where each of the three features can be varied in time and amplitude independently. This starting point immediately showed great results when simply used as a modulator for white noise. Approximate ratios of $3:2:3$ sounded right for walking, $3:1:3$ for running, and $1:2:3$ was good for walking slowly uphill or in difficult(snow) conditions.

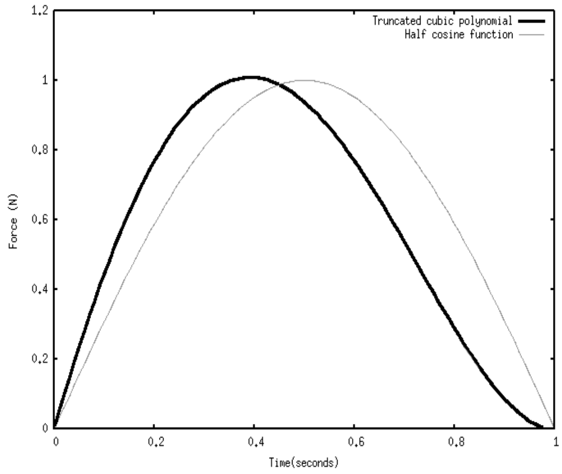

Figure 3: Polynomial segment.

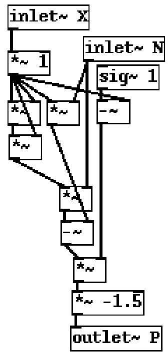

Figure 4: Pd polynomial curve shaper

4.2 Control signal by polynomial approximation

Experimentally the cosine method proved effective but unrealistic. It seemed too uniform and mechanical and somewhat like the shoes were extremely soft. Some control of the slope seemed necessary because most of the effective synthesisers were found to operate from the first derivative of the GRF, representing the work done where changes in energy correspond to excitement. To correct the curve to more closely fit the results of Adamczyk, Collins and Kuo [4], a polynomial of the general form $k(nx^3 - nx^4 - nx^2 - nx)$ was used as a function to shape a normalised phasor over each of the three force phases. The difference between the sinusoidal curve and this polynomial for $N = 3.333$ is seen in `Fig.3`. Notice that the curve is pushed backwards and can grow faster or slower than the cosine function over the same range for appropriate values of N. The implementation, rewritten in a form $-1.5((NX^3) - (NX))(1 - X)$ allowing zero adjustment is shown as a Puredata abstraction (`Fig.4`). Fixing the zeros where they are with this range means that growth is faster for higher amplitudes, a nice feature that seems to correspond well to inelastic collisions where crushing and deformation are involved. X is the time index from the phasor and N is the modulation index. The superposition of three time shifted segments that approximates our GRF is seen in `Fig.5`.

4.3 Synthesis

An approximation to gravel is achieved by a cheap granular method using a filter and noise source. A resonant filters cutoff is modulated by the absolute value of a low passed version of the noise. The signal path of the filter itself is high passed white noise. Applying a scaling factor to the amplitude of the noise and the cutoff frequency of the low pass filter one obtains a signal where the density and colour of the grains can be adjusted. Several important variables have been examined that are useful in a force driven model. A threshold value to cull weak sounds or forces below the threshold for frictional movement is very helpful. The second is the mapping of GRF to density which approximates the movements of small particles. With frequency as the square of GRF and density as unity a good result is achieved

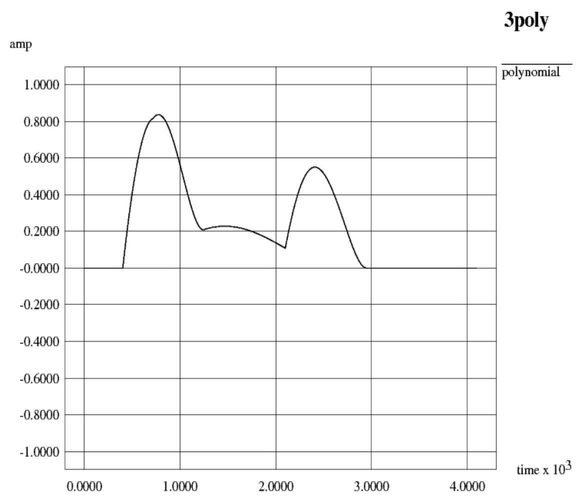

Figure 5: Superposition of polynomial segments

somewhere around 20 grains per second between 600Hz and 1.2KHz. The completed Puredata code is shown in `Fig.6`. Each of the three contributory curves is handled by one of the `[pd polycurve]` units. The scaling value N is brought out on a fader, one for each of heel, roll and ball.

Stone and concrete surfaces can be mapped with the square of the power (rate of work) to envelope a noise burst to an appropriate formant filter for that surface. Metal and wooden surfaces can be similarly synthesised using a properly tuned set of filters or allpass units. When including the heel/ball ratio as a function of speed some dramatic effects that make the platform seem to incline occur. With grass, dirt and gravel textures it was found best to drive two or three different synthesisers in parallel and mix their outputs to get a slowly shifting ground texture moving between sand and stony ground. A brightness or damping control made by decaying higher frequencies faster had a good approximation to surface hardness when using this method.

4.4 Further work on texture synthesis

Although it should be possible to adapt a single synthesis algorithm for a wide range of surfaces the goal of this experiment is to obtain the correct excitation curve. So as a practical concession different synthesis methods were used for each material, partly for expediency and partly to best test the range of audio signals obtainable from the control signal. One general feature of all texture synthesisers tried is to use grain envelopes. This is useful because many surfaces are not clearly one material and it allows us to blend aggregates like dirt, stones, grass and sand in varying degrees to get a smooth transition as the actor walks across changing surfaces. Excitation types are soft impact, scraping and crushing. The first corresponds to a gentle pulse while noisy signals are appropriate for frictional excitation. Converting the GRF signal into contact impulses is achieved by rectifying its derivative, while the GRF signal is used directly for frictional excitation. For metal surfaces like walkways and ladders which continue to vibrate after the excitation is removed a separate amplitude curve is obtained. For sand, gravel, hard ground, wood or stone various degrees of damping are applied by filtering and re-normalising the GRF curve. One unique case is that of snow. Most materials can be taken to be elastic and symmetrical in the signals they produce according to pressure, but snow (and perhaps some other materials) are permanently deformed into ice by pressure causing a squeaking sound. Ice and wood also have unique features that are non-linear and asymmetrical, they may creak and groan at specific pressure thresholds. Effective synthesis of snow and ice seem to be quite challenging cases. Frequencies corresponding to the material types were obtained by spectral analysis of examples from film and game audio using a high resolution sonogram in the Snd editor. As few as 5 to 10 peaks are adequate to obtain reasonable sounding results. Though this analysis is crude it is deliberately so for reasons of efficiency. The success of the method relies more on the envelope shape obtained from the GRF curve than the spectral accuracy of the grains. Future work will concentrate on efficiently generating more complex spectra using FM or other non-linear methods.

5. RESULTS

With the three faders attached and two instances of a "foot" running on opposite metronome cycles a range of walking speeds can be be explored. One interesting result is the high degree of realism implied by modifying the slopes as a function of change in actor velocity. The sound of someone sprinting away or screeching to halt is a subtle psychoacoustic clue given in the ratio of force curves in the footstep. For example, slowing down requires negative work and pressure is shifted to temporarily to the ball phase. Another exciting result was the range of surface synthesisers that could be adapted to create good results. Although a greater improvement in CPU efficiency was anticipated tests showed the polynomial method using 4 multiplies and 4 addition operations is only marginally more efficient than employing three cosine functions. This may be a feature of Puredata which already computes a rather efficient cosine approximation, or errors in the calculation due to the small number of instances measured. The success of the experiment is clearly the subtle but acoustically significant effect of having control over a curve obtained by polynomials.

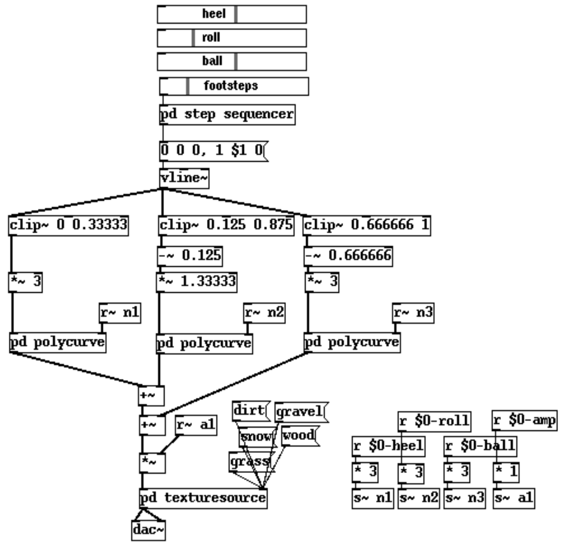

Figure 6: Footsteps by polynomial superposition.

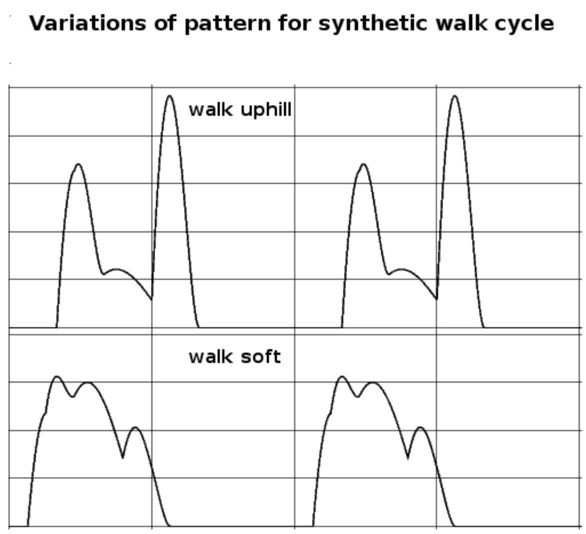

Figure 7: Synthetic force curve by polynomial superposition.

6. CONCLUSIONS

Fairly sophisticated footstep pattens (`Fig.7`) can be approximated by a series of discontinuous polynomial functions on a single duty phasor. By changing the influence of each of three phases it is possible to mimic the variables for workload, weight and speed. Actor velocity is best treated as a continuous control variable for all practical purposes. If it is found necessary to delineate modes of movement this is most easily achieved by an intervening non-linear function. For application to procedural audio in a physics driven environment a continuous force control signal can work with relatively few additional variables like speed, mass and inclination to produce useful synthesis parameter data.

Puredata file: `http://www.obiwannabe.co.uk/html/papers/pdcon2007/footsteps-poly.pd`

Sound example: `http://www.obiwannabe.co.uk/html/papers/pdcon2007/gravel-walk.ogg`

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