Fourier Series Character Animation
Adapting and Generating Actions

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Abstract

In this paper, we present a method for synthesizing and analysing rhythmic character motions using signal processing methodologies, such as, the Fourier transform. While the Fourier transform has proven itself in many fields of engineering and computing for providing an uncumbersome and efficient method of representing signal or functional information in the frequency domain. As we show in this paper, applying this concept of converting character joint signals to the frequency domain, allows us to categorise different motion elements. For example, walking styles, such as, stylistic qualities that include happy or tired, that we are able to identify - and either filter or amplify. Additionally, the data from the transform provides a set of ground control parameters for recreating animations with similar characteristics. We show how the Fourier transform proposes a novel alternative to pure data-driven methods and how a hybrid system in combination with an adaptable physics-based model can be used to synthesize aesthetically pleasing motions that are controllable and physically-correct. We focus on demonstrating the enormous rewards of using the Fourier transform for motion analysis and in particular its application in extracting and generating unique motions that possess personal qualities.

1 Introduction

Character Animations A method for 'measuring' or 'filtering' specific types of stylistic character motions (e.g., tired or energetic) is challenging and important. This includes, a method that is applicable to both human and non-human character topologies (e.g., bipeds, cats, and dinosaurs). Once we are able to identify motion characteristics, it would aid the generation of unique character animations that are able to adapt to unforeseen circumstances in a natural and life-like manner. Combining a solution with an adaptable physics-based model would result in autonomous characters with the ability to maintain a physically-correct pose while encapsulating and embedding behavioural and stylistic quantities into the generated motion. For example, characters with the ability to adapt to unforeseen circumstances without artistic intervention, such as, navigating complex terrain while remaining balanced and upright.

Challenges Characters are highly ambiguous and typically possess a large number of degrees of freedom. Ideally, we seek a solution with a reasonable computational cost (i.e., solvable in a viable time-frame and ideally be scalable with the character and motion complexity). As we are aware, organic creatures are typically complex and unique individuals, making it difficult to quantify, extract and measure 'specific' behavioural motion qualities (e.g., such as, tired or happy). Additionally, the motion qualities will be mixed together with a variety of diverse actions (e.g., walking or eating). We must also be aware that simply extracting or filtering a specific motion component from an animation may results in a solution that is no longer physically correct or natural looking. For instance, simply attempting to extract the tired component of an animation may result in a walking motion that is strange, while violating physical constraints, such as, foot placement locations and balance. Finally, real-world character motions are 'self-driven'. That is, the character's motions, are accomplished using muscles which drive joint torques and propel the body via contacts with the environment to achieve the final action. This is an important quality, that we want to capture in the final solution, since we want to avoid the creation of puppet-like doll motions (i.e., floating puppets).

Traditionally Animation systems are broadly categorised into three main types, signal data-driven (e.g., key-frame libraries), kinematic, and physics-based. Then there are the hybrid-solutions that try to resolve limitations or exploit specific features by combining multiple techniques into a framework. To begin with, the most popular character animation systems evolve around pre-recorded key-frame solutions using blending and warping techniques to create the final motions [Kovar et al. 2002; Wiley and Hahn 1997; Rose et al. 1998]. These solutions have the advantage of being simple, efficient and the able to create a diverse range of animations to meet even the wildest artistic imaginations. However, the limitations of key-frame methods are they requires a large inflexible database of animations. These animation libraries are targeted to specific situation and character topology. However, kinematic solutions in part build upon and complement key-frame based methods by adjusting character poses to meet specified pose constraints (e.g., changing joint angles to fit the situations). This includes techniques, such as, inverse kinematics, which ensure a character's foot is at a particular location at a chosen time and does not slip and slide. Finally, both data-driven and kinematic methods lack any 'physical' knowledge, such as, balance or energy. Hence, physics-based solutions us concepts from classical mechanics to simulate body motion using forces and torques. Mimicking the real world to produce highly responsive and realistic results. The largest drawback of physics-based character models is the overseeing control mechanism. Emulating controlled autonomous motions that are able to adapt to different situations is difficult to achieve.

Our Solution Our approach uses signal analysis concepts to categorize and measure rhythmic character motion qualities. The solution works by combining fundamental qualities of rhythmic motions, such as, walking or dancing, that possess stylistic qualities which input into a physics-based training simulation to synthesize motions that are both aesthetically pleasing and controllable but adaptable and customizable. Essentially, we perform two steps, firstly, we analyse, identify and quantify different motion qualities. Secondly, we use the extracted information to train a heuristic physics-based algorithm to reconstruct targeted motions.

Contributions The key contributions of this article are: (1) Combination of Fourier series, evolutionary concepts, and physics-based simulation methods to adapt and generation character animations. (2) Extract and quantify specific types of motion components into their frequency components. (3) Removal and addition of motion qualities while maintaining a physically correct animation (filtering animation components and reconstructing an animation that is 'correct'). (4) We are the first to look at 'indirect' signals, such as, foot placement transitions and centre of mass trajectories, compared to just analysing the joint angle signals. (5) Traditional motion filter systems have used kinematic solutions to re-correct animations, such as, end-effector orientations and locations, compared to our approach, which adapts coefficient using a heuristic algorithm that drives a physics-based model.

2 Related Work

The exciting area of character animation is an active multi-discipline field. To help show where our work sits in relation to other research, we divide the concepts into categories. This includes, motion signals (key-frame libraries), kinematics, and physics-based solutions. In addition, we also review hybrid systems, that build upon the core categories to form building blocks that attempt to resolve inherent shortcomings and limitations similar to our approach.

Motion/Kinematics Bruderlin and Williams [Bruderlin and Williams 1995] decomposed motions into their respective frequency bands as a form of motion signal processing and also allowed to control the blending gains for the bands. Unuma et al. [Unuma et al. 1995] interpolated and transitioned between motion sequences by using a Fourier series expansion. Rose [Rose et al. 1998] proposed to align key events in a blended motion using radial basis functions and time warping methods. Wiley [Wiley and Hahn 1997] re-sampled motion examples with linear interpolation and time-scaling proposed, in order to create a larger motion library. Rearranging pieces of previously recorded motions is another approach of motion capture editing. The main problem here is to find a re-arrangement that meets certain criteria. Different methods for performing the combinatorial search of animations have been presented [Arikan and Forsyth 2002; Tanco and Hilton 2000; Lee et al. 2002]. Kovar [Kovar et al. 2002] present a popular method for mixing and managing animations known as motion graphs. One overall issues with blending methods is they cannot truly synthesize novel body configurations, because every frame is taken from the original motion collection.

Physically-Based Wooten [Wooten and Hodgins 2000] created parameterized controllers for simulated leaping, tumbling, landing and balancing, and concatenated them to create gymnastic behaviors, such as, diving and flipping. Kenwright [Kenwright et al. 2011] constructed low-dimensional models based on research from robotics and biomedicine to emulate fundamental motions (posture and stepping mechanics) that were able to adapt to unforeseen circumstances, such as, pushes and changing terrain in real-time. Hodgins and Wooten [Hodgins and Wooten 1998] the topic of animating human athletics is detailed and a method presented to animate human athletics in respect to the physically laws. Running, gymnastics, an diving motions are generated by using hand-tuned, state machine-driven controllers. Lazlo [Laszlo et al. 1996] presented an approach with a limit cycle control to produce physically realistic, periodic walking and running motions. Faloutsos [Faloutsos et al. 2001] added a repertoire of autonomous motor skills to a virtual stuntman, such as, recovery motions and reactions to falling. Kenwright [Kenwright 2014] evolutionary animations of low-dimensional planar character using a geometric approximation analogous to our technique, however, the geometric parameters are solely generated from the fitness function. Our work, at its heart, has physics-based model, which is used to determine the quality of the final motion using an adaptable procedural algorithm. For example, see Figure 1 for a visual illustration showing trade-offs between an artistic and pure physics-based system.

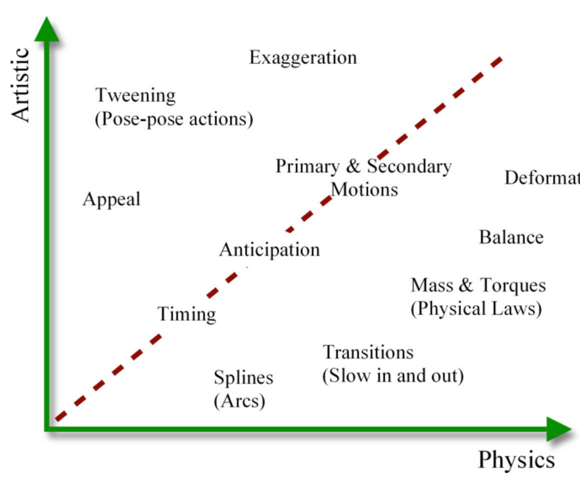

Figure 1: ***Animation Features*** *- Trade-off between artistic control and physical correctness.*

Hybrid Solutions As illustrated in Figure 1, an animation solution needs to balance between a physically correct model while allowing artistic intervention. This is accomplished through hybrid solutions that mix motion data/kinematic models and physics-based solution. Zordan [Zordan and Hodgins 2002] demonstrates the combination of motion capture data with a physical model. Arikan [Arikan et al. 2005] to create physically plausible motions for pushing people around situations. Playter [Playter 2000] combined a physics-based simulation and motion capture with a controller for running motions. Pollard [Pollard 1999] introduced low degree-of-freedom machines for scaling basic human motion, such as, running. Popovic and Witkin [Popović and Witkin 1999] proposed a physically-based motion transformation by using a low resolution physical model applied to running and jumping motion data. Rose [Rose et al. 1996] generate efficient motion transitions using inverse dynamics and space-time constraints by finding a minimum energy solution. Kokkevis et al. [Kokkevis et al. 1996] presented user controlled physics-based animated articulated figure. The goal is to modify motion to include physically based reactions to gravity or external forces. Our solution combines both data-driven and physics-based analogy. Whereby the data from animation libraries provides training information for the physics-based system.

3 Method

The following sections describe our method for analysing and synthesizing specific character motions. We use signal analysis concepts to extract approximate parameter limits that feed into a heuristic physics-based training algorithm.

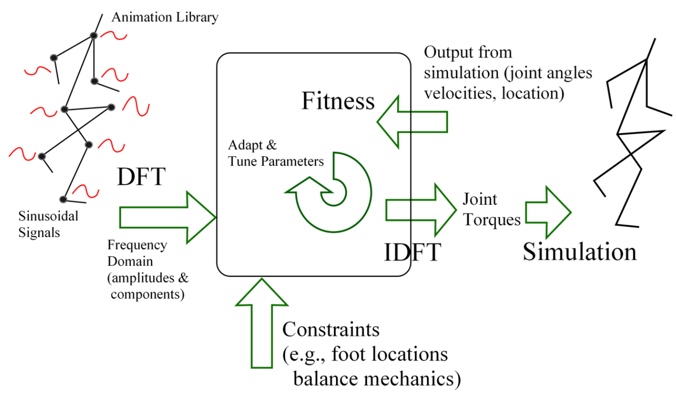

Figure 2: ***Interconnected Components*** *- Overview of the interworkings of our implementation for synthesizing articulated character motions (importantly, all waveforms, no matter how complex, may be represented as a sum of simple sinusoids of different frequencies).*

Rhythmic (cyclic) are at the 'core' of our approach - animations, such as, walking and running We look at an animation and try and identify motion 'slices' (i.e., components of a motion that have a repetitive quality). Dissecting a motion so that we are able to reconstruct the original motion 'or' more importantly, construct new motions with the underlying life-like qualities, similar to how basic animation techniques blend and mix a variety of animations together. Finally, we must also note 'secondary' motions, such as, swaying and breathing, which are less subtle, but possess rhythmic qualities that are important in realism. Neglecting secondary rhythmic motions causes the final motions to appear non-organic or robot-like.

Show what the joint angle motions look like for different characters - share similar 'frequencies' See how all the different joint angles come together to form the final motion. We must remember that a character action, even a simple one, such as, walking, the interconnected joints are highly coupled and propagate information that is important. Identifying the primary joints that contribute to the core motion (e.g., knee), while secondary joints (e.g., neck or wrist) play a smaller part. For example, which joints could be removed from the skeleton to reduce the degrees-of-freedom (DOF) and the complexity and computational cost.

Character complexity (39 degrees of freedom (DOF)). Sufficient DOF to capture the fidelity of motion present in the real-world. The character limbs are rigid and connected by joints. The only parameters are the joint angles. As time changes the joint-angles changes. The time changing joint angles form a sequence of sinusoidal signals.

Fourier Series The fundamental concept is built around the idea that any signal shape can be represented by a sequence of sinusoidal functions (even square waves). A re-scaled version of the Fourier series concept [Unuma et al. 1995] presents a simplified form while encapsulating the central concept of summing sinusoidal signals to reconstruct joint motions, as shown below in Equation 1.

$$\theta(t) = A + \sum (B_n \; sin(C_n \; t + D_n)) \tag{1}$$

where A, B_n, C_n, and D_n are unknown parameters that need to be found for each changing joint-angle.

Conceptually, the idea is sound - however, the challenge is finding suitable parameters for a specific motion. Each time the character topology or navigation environment change the parameters must be re-calculated. Kenwright [Kenwright 2014] was able to use a genetic algorithm to find the parameters based on fitness criteria, such as, balance mechanics and stepping information. However, this approach is highly dependant on the fitness function and can take a long time to converge on an acceptable solution. Our solution, uses the Discrete Fourier signal analysis techniques to analyse motion-capture data initially to find an area or range within which the values sit. This is to categorize the motion into its fundamental parts (e.g., which signals contribute towards locomotion and which signals to behaviour).

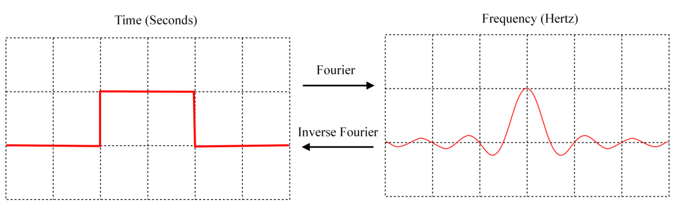

Figure 3: ***Fourier Series*** *- Any waveform (a function or signal) is able to be represented by its alternate frequency representation - this is characterized by sine and cosines (i.e., the waveform can be re-written as the sum of sinusoidal functions).*

Too Many Parameters How do we define which parameters control which motions? We must also be aware that the parameters a highly coupled and non-linear. For example, changing one parameter may influence the motion of the whole body and multiple secondary motions in a non-linear way. We are able to sort the sub-signal components into priority of magnitude. Since the ideal Fourier Series is an infinite collection of sinusoidal signals, which we truncate to the top five harmonics. This enables us reduce the number of parameters, while still being able to reproduce the original signal without too much loss of detail. For example, Unuma et al. [Unuma et al. 1995] typically used 3 sine functions with a maximum of 7, to imply that basic human locomotions are characterized with the small number of Fourier coefficients and phases in the Fourier functional model. However, the approximation is scalable, so as computational power increases and the need for higher fidelity, additional harmonics an be added back in.

Discrete Fourier Transform (DFT) and Inverse DFT (IDFT) The **Discrete Fourier Transform (DFT)** to break down a signal into its components - i.e., time to frequency domain - allows us to extract a 'base' set of parameters to recreate the motion signal we are analysing. The **Inverse Fourier Transforms (IDFT)** lets us re-create the original signal. For example, we can filter or remove specific components in the frequency domain. Reconstruct the original signal and see how will change the joint motion.

Visually coloring the equation to enhance the interpretation and understanding of the Fourier Transform is shown below in Equation 2:

$$DFT: \quad X_k = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x_n e^{-i 2\pi k \frac{n}{N}} \tag{2}$$

To find the energy at a particular frequency, spin your signal around a circle at that frequency ,and average a bunch of points along that path.

where N = number of time samples, n = current sample we're considering $(0..N-1)$, x_n = value of the signal at time n, k = current frequency we are considering (i.e., 0 Hertz up to N-1 Hertz), X_k = amount of frequency k in the signal (amplitude and phase, a complex number), The $\frac{1}{N}$ factor is usually moved to the reverse transform (going from frequencies back to time), $\frac{n}{N}$ is the percent of the time we have gone through, $2\pi k$ is our speed in radians / sec. e^{-ix} is our backwards-moving circular path. The combination is how far we have moved, for this speed and time.

Vice-versa, the sequence x_k can be calculated from X_k using the Inverse Discrete Fourier Transform (IDFT) as given in Equation 3. In general, both x_k and X_k are complex with the component providing signal information, such as, phase and magnitude.

$$IDFT: \quad x_k = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k e^{\frac{+i 2\pi n k}{N}} \tag{3}$$

Approx '5' sin waves to create an animation that is aesthetically pleasing If we take an original animation, extract the Fourier parameters and reconstruct the original motion using only 5 parameters it provides an acceptable solution.

Heuristic Search We employ an evolutionary algorithm to adapt and adjust parameters to meet particular goals, such as, foot placement error and balancing characteristics, while the extracted Discrete Fourier Transform (DFT) coefficients form a rough guide and range with stylistic information.

Actions & Motions Distinguish what we mean by an 'action' and a 'motion'. An action has purpose and results in the accomplishment of a task, such as, picking up a chair. A motion is simply the movement through space. Actions are performed via different motions (i.e., an action is composed of motions) [Smyth and Wing 2013].

Physically correct We don't adjust the 'joint' angles directly, as in Unuma et al. [Unuma et al. 1995], instead we apply joint torques. Motions are only achieved through the physical interaction with the environment, such as, a character pushing their feet on the ground to raise themselves up.

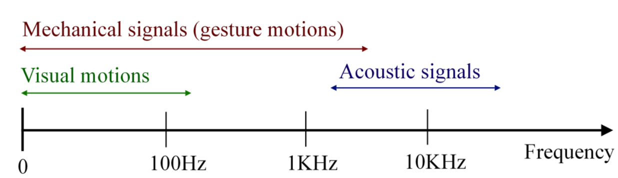

Figure 4: ***Motion Frequency Range*** *- Categorize and identify different motions frequencies and their corresponding connection. For example, hand motion gestures and small rhythmic movements from breathing and talking possess higher frequency components compared to casual motions, such as, walking and climbing.*

4 Experimental Results

The implementation was in the form of a tool that an artist could editor and create motions for different situations. For example, the user could load in a skeleton rig, specify the number of Fourier components for each joint-angle, mass distribution, fitness search time (e.g., analyse generated motion over five seconds). Experiments included, simple low-dimensional bipeds, cats, and random hopping creatures. Figure 5, shows a simple stepping model, we render large number of instances which are generated and re-run repeatedly for the duration of the time-slot to train the parameters and achieve the final motion.

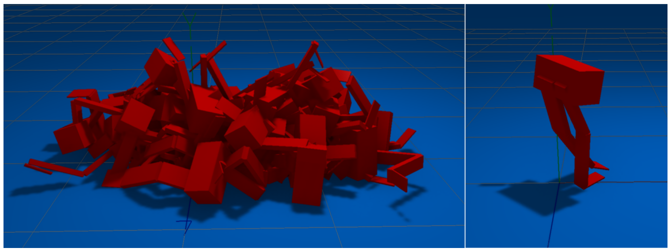

Figure 5: ***Stepping*** - *Experimenting with different model topologies, such as, a pelvis and legs, to explore creating simple stepping motions. The illustration shows the evolutionary search population running multiple instances to find the 'fittest' parameters that match the desired characteristics.*

The bandwidth of motion capture systems is typically limited between 10 to 300 Hz with degrees of freedom ranging from 10 too 100. However, the motion capture data provides suitable approximations for analysing and synthesizing aesthetically pleasing results. Understanding and measuring the essential components of movement. Additionally, mixing in random higher frequencies adds in other elements less obvious characteristics to the motion, such as, breathing and swaying [Kenwright 2012] to make the final motion more realistic.

5 Conclusion

This paper has presented a novel tool for building upon traditional animation approaches (i.e., key-frames and motion-capture data) by analysing and creating animations for different situations, such as, character topologies and dynamic environments. Additionally, we provide a method to identify behavioural motion types, such as, worried and tired, so they can be integrated in with the final solution. The work would eventually allow animation solutions to be broken down into different classifications, such as, a primary motion (e.g., walking) and a secondary stylistic motion (e.g., happy or sad). Instead of having a repertoire of walk motions with a diverse range of qualities (walk-happy, walk-sad, and walk-tired).

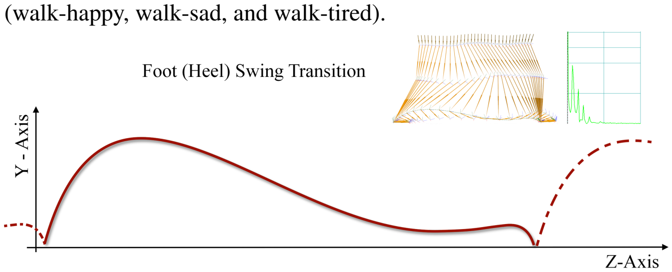

Figure 6: ***Swing-Phase*** - *Modelling simple transitions, such as, foot-heel patterns, using Fourier series methods, enables us to create more natural looking animations. With the centre-off mass we are able to generate stepping mechanisms that remain balanced [Kenwright et al. 2011], in combination with inverse kinematic solutions. However, the final motions lack an 'organic' element, such as, motion transitions. Note, we analyse the foot transition trajectory not the individual body joints.*

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