The study of motion

It is always fascinating to watch the motion of objects in the world, particularly the movement of living creatures. The crawl of a worm, the slither of the snake, the leap of a gazelle, the run of a dog, the gallop of a horse or the walk of a human, all look amazingly simple and beautiful, yet involve extraordinary skill in muscle coordination and balance. Reproducing even the simplest of these movements by mechanical, or other means has always been a challenge. This in part explains the tremendous appeal that Disney animations hold for young and old alike, or the effect that a moving limbed toy has on any child. Computer animation is primarily concerned with generation of the motion of virtual creatures moving around and interacting with a virtual world such that the movement appears physically realistic and is generated in a computationally efficient manner.

Apart from computer animation, motion is studied and modelled in a number of other disciplines like robotics, biomechanics, control theory and artificial life. These disciplines has their own distinct emphasis in the study of motion as discussed below, but most developments in these disciplines are bound to find application in computer animation.

Motion planning and motion control are central areas of research in robotics [22]. Forward and inverse kinematics, as well as forward and inverse dynamics are important concepts from robotics that have a direct application to the animation of articulated figures. Robots inhabit a more complex physical world
than their synthetic counterpart, and must sense the environment and react to it in real time. However, the movement of robots is not just simulated but physical and is brought about by internal force generators and actual physical interaction within physical world.

Biomechanics is the study of the mechanical bases of human and animal motion [19]; with the central focus being on musculotendons which act as the main force actuators to bring about motion. Muscles have many properties that influence the type of motion produced. Biomechanics is concerned with a study of these properties as well as with the investigation of schemes for controlling muscles to yield desired motion. Traditionally, studies in biomechanics have focused on a single muscle or a single joint.

Conventional control theory addresses the problem of motion control, but of rather simple systems [57]. For more complex systems, difficulties are primarily due to the non-linearities involved. The field of control is additionally concerned with the issue of proving stability and performance under all conditions. Most systems that are studied in control theory are simple, in comparison with the motion control systems needed for typical animated figures.

Artificial life is a new science dedicated to mimicking the emergent behaviour of living systems in silico. Instead of trying to simply replicate the effects of living systems, artificial life researchers attempt to build these behaviours from bottom-up, much in the style that nature itself does. A typical artificial life approach begins with biological behaviour such as reproduction, evolution and locomotion and attempts to extract simple local rules behind that behaviour [104]. Many of the simulated creatures are defined by compact code, which subsequently determines the creatures' behaviour when placed in an environment. Once again most creatures being experimented with are still too simple to be interesting enough for the purposes of animation.

The movement in animation is really just an illusion; made possible because of the biological phenomenon of persistence of vision. A series of images slightly differing from each other are shown in rapid succession. The eye/mind blends them together to result in the visual illusion of movement or change. Typically
24 to 30 frames (images) per second are shown. Animation is primarily concerned with the synthesis of these images at discrete times and strictly speaking does not mandate the modelling of continuous time varying motion. However, in computer animation we find it convenient to model motion as a continuous function of time and generate the individual frames by appropriately sampling this function.

**The motion synthesis problem**

Movement or motion is a dynamic phenomena - it is the change in spatial configuration of an object over time. The spatial configuration of an object is defined geometrically. A simple object like a pen is completely defined by the position of a single point on its body say \((x_p, y_p, z_p)\) and its orientation \((\theta_x, \theta_y, \theta_z)\) in three dimensional space. More complex legged objects are defined as articulated bodies composed of links that are connected to each other via joints. However, in order to contain the complexity, in most studies rigid articulated bodies are used for modelling the motion behaviour of legged creatures.

*Degrees of freedom* (DOF) constitutes the minimal set of parameters needed to completely specify the configuration of a body in space. Degrees of freedom are also known as generalised coordinates. Thus the spatial configuration of the pen in 3D has 6 DOF. With just 6 parameters, the pen can be moved to any desired point and oriented in any desired direction in space. An articulated body has more DOF depending on the number of links, joint types etc. Consider for example the planar articulated body with 3 links and 2 rotary joints as shown in Figure 0.1. This simple body has 5 degrees of freedom. Human bodies are amongst the most complicated of articulated bodies. Typically, the human body has about 200 degrees of freedom [110].

A universally accepted convention is to consider degrees of freedom as constituting a vector and use vector notation say \(X\) to denote the spatial configuration of a body. Hence the motion of the body over a time period \(T\) would be denoted by \(X(t), 0 \leq t \leq T\).
A rather simple definition of the synthesis problem is as follows:

Given the geometry of an articulated body, say $X$, a desired type of movement say walk and a time period $T$, determine $X(t), 0 \leq t \leq T$.

The above definition hides the enormous underlying complexity in this problem. Certainly physics is involved; gravitational and other forces have to be considered. The movement of a pen dropped from a height of say, four feet from the ground is not arbitrary but completely determined by the properties associated with the pen, such as its mass, moment of inertia, coefficient of restitution etc. Animators take years before they acquire the necessary skills to predict the spatial configurations of objects at any time for generating a specific movement. Living creatures are active articulated bodies that can bring about their own motion through internally generated forces and interaction with environment like the wall or the ground. For such bodies, the motion synthesis problem becomes orders of magnitude more complex. It is only in very recent times with easy availability of computing power that the studies of motion of such complexity are being undertaken in the different disciplines listed above.

Traditionally, in animation the motion synthesis problem is tackled using a technique known as key-frame animation. In key-frame animation, the animator only describes a set of "Key-frames" from which the system can geometrically interpolate each DOF independently to automatically generate all the inbetween frames needed. There are two major problems with key-frame animation. Firstly it puts a large burden on the animator by requiring the adjustment of too many parameters at very fine levels of detail. For a reasonably detailed figure with 30 DOF, a minute of animation with a key-frame, say, every quarter of a second, would approximately require eight thousand values to be specified. This is perhaps an impossible task. Secondly, to generate very convincing looking motion, the animator must have a very good understanding of the motion and also possess artist like skills, for resynthesizing the internalised motion. Therefore more often than not, even after many trials, key-frame synthesized motion tends to look unrealistic and puppet like.
In the late 1980's, researchers working in the field of computer animation were convinced that if the animation has to look realistic, the physics behind the motion has to be taken into account [3, 105, 52]. This is typically done by augmenting the traditional geometric model to include other physical characteristics that computers can use to compute motion. These physical characteristics are mass of the body, its moment of inertia, external forces such as gravity, friction etc. The idea is to incorporate appropriate physical complexity and realism of the behaviour into the model itself, rather than requiring that it be imposed by the animator. Initial results on incorporation of physics to produce realistic movements were very encouraging.

In physically based animation, the task of synthesizing motion is accomplished in several steps. The first is to create a suitable geometric model of the articulated figure by defining the geometry of each link and its relation to the rest of the body. The second step is to supply physical parameters which include, mass, centre of mass and moment of inertia for each link. The third step is to define control parameters that will determine the necessary force/torque function which will bring about the desired motion. In the fourth step the equations of motion are assembled and solved using numerical techniques to obtain the position of the object over time. In the last step, individual images (frames) are rendered.

Currently there are two approaches in physically based animation. They typically trade off computational work for autonomy of movement versus manual work for controllability of movement.

The method of space-time constraints [108] and space-time windows [20] belongs to the first category. It poses the motion control problem in terms of trajectory through space and time which is subject to the constraints of physics and the constraints of the desired motion. This approach has close ties to keyframing. The second approach involves creating a controller which produces motion by directly supplying actuating forces and torques [101, 81, 49]. A parameterized controller results in a compact representation of motion. The controller is typically synthesised by searching in the multi-dimensional parameter space of
urally specified in the form of desirable set of motion feature values. Further, with a given motion feature vector as input, the actual desired movement can be automatically synthesized by the use of appropriate optimization based search procedures in the space of motion controllers.

It is important to note two aspects of the problem of searching for an optimal controller for a specific movement by an articulated figure:

- The search space is large and multimodal. The number of locally optimal solutions far exceeds the useful solutions which typically occupy small portions of the search space.

- The search space may be discontinuous. Small changes in the control parameter values may lead to a large change in the fitness value.

As a consequence motion synthesis for articulated figure is compute intensive and needs efficient implementations.

**Implementation and experiments**

As part of this research a fairly elaborate implementation has been carried out to substantiate the above thesis. The implementation enables us to test out the automatic synthesis of motion for planar articulated bodies by specifying desirable feature values from a predefined set of motion features. The automatically synthesized motion is played back in real time on the computer display screen. Our implementation includes the following:

1. accepts geometric definitions of an articulated body
2. models the ground and interaction with the ground
3. formulates equations of motion
4. simulates the motion for a given set of controller parameters
5. uses the desired feature values and constructs the fitness function that is used by a genetic algorithm to search for the optimal controller in the controller space.

Figure 0.2 shows an overview of the different components of our system.

Since the entire process is very demanding on computer time, the search process has been parallelized to run on a network of CPUs. The overall performance and the synthesized movements are extremely encouraging.

**Thesis Organization** Chapter 1 is a brief introduction to the main goal of all computer animation – the synthesis of motion of virtual objects/creatures moving and interacting in virtual environments. The importance of physical correctness and realism in synthesized motion is clearly brought out. The chapter includes a small comparative analysis of the approaches to the study of motion in computer animation and in other disciplines like Robotics, Biomechanics, Artificial life and Mechanical simulations. It also gives an overview of the different approaches to the automatic synthesis of physically correct motions, the problems present in these approaches and the solution methodology proposed by us.

Chapter 2 is a comprehensive review of all known methods in computer animation for generating animated sequences involving articulated figures. Both kinematics and dynamics based techniques are discussed. The various approaches being pursued for the automatic synthesis of physically based motion are presented and motion synthesis through the automatic generation of optimal motion controllers is identified as the most promising approach to date.

In chapter 3 we discuss in detail all major aspects of optimization techniques as applicable to the motion synthesis problem. The aspects provide a framework along multiple dimensions like search space, task goal, constraints, dynamics simulation, and search algorithm, which enables us to concisely review the existing optimization methods and also any new developments that may take place in the future in this optimal motion search area.

Chapter 4 describes the importance of external object interaction in the move-
Figure 0.1: A planar articulated body with three links and two rotary joints

Figure 0.2: System Configuration
ment of an articulated figure. Basically all external interaction results in forces and torques that get applied to the moving figure. Collision forces are specifically the most important amongst these. The chapter reviews the collision detection and collision response problem and strategies in use for finding solutions to these problems. The different types of contact or collision like the colliding contact or the resting contact and methods for handling these are also reviewed. Finally the difficulties of modelling frictional contact are presented.

Chapter 5 addresses the primary thesis of our research — the automatic synthesis of motion through the specification of features. To begin with, we introduce the notion of motion features and formulate their specification as computable functions that take complete motions as their arguments. We formulate the performance metric that uses these feature values. The performance metric formulation is such that its value is optimal when the motion, has the specified features. Choosing the domain of gaits of legged creatures — a topic very well studied in different disciplines — we define a set of motion features that could be specified by an animator to obtain different kinds of gaits.

Chapter 6 describes our implementation and also the results from the different experiments that we conducted for synthesizing different kinds of movements for virtual legged creatures. As part of our research we have created an integrated simulation environment. The overall architecture and the different components that make up this environment such as the physical, geometric and feature model, the simulator and controller synthesizer are briefly described. Since the total computational effort involved in the motion synthesis task is excessive, we have parallelized the search process. This chapter also describes this parallel global optimal search algorithm based on evolutionary programming (a type of genetic algorithm), known as the stochastic population hill climbing (SPHC) algorithm. The parallel SPHC has been implemented using the parallel virtual machine (PVM) system. Finally the chapter describes in detail the structure of 3 virtual creatures (a single legged creature and 2 two-legged creatures), and the results of our experiments in automatically synthesising different types of gaits for these virtual creatures by the method of motion feature specification.
Figures 0.3-0.5 shows some animation sequences synthesized using our implementation.

![Animation of Mr. Luxo](image1)

**Figure 0.3:** Mr. Luxo, a lamp like creature hopping

![Animation of Mr. Pogo](image2)

**Figure 0.4:** Mr. Pogo, a dog like creature walking

![Animation of Mr. Walker](image3)

**Figure 0.5:** Mr. Walker, a human like creature walking

Chapter 7, the last chapter of our thesis analyses three major aspects of our work. The basic approach to solving the problem of motion synthesis, the specific solution methodology proposed in this research and the implementation and experiments carried out by us. Specifically the chapter highlights the significant contributions, some deficiencies/limitations, future extensions possible and some open problems in this area.