Chapter 1

Introduction

The movement of objects in this world has always fascinated mankind; whether it is the movement of a planet, the flight of a ball or the walk of a living creature. For centuries, philosophers, physicists and mathematicians have all attempted to study and theorize the motion of objects in the world. Thus the science of mechanics concerned with the motion and equilibrium of masses is that branch of physics which is at once the oldest and also the most fundamental, and is therefore treated as introductory to other departments of physics. It was not however until the 17th century, that a robust set of physical principles were put forward to explain the mechanics of everyday objects, when Issac Newton published his three laws of motion (in Principia) in 1687. Newtonian physics has been one of the grand success stories of science. The Newtonian paradigm has maintained its utility till date despite stunning conceptual advances from relativistic and quantum physics developed by Einstein and others. The study of Newtonian dynamics is no longer an active area of research in physics. Instead, research efforts have branched into newer disciplines such as robotics, biomechanics, physically based computer animation, and artificial life. Physically based computer animation is the primary area of focus in our research. However, we also briefly describe in this chapter the distinct emphasis that some of the other disciplines have in their study of motion. Developments in all these fields are bound to find application in computer animation as well!
1.1 Computer Animation

The primary purpose of a computer animation system is to provide assistance to the human animator in synthesizing the movement of an object such that the resulting motion appears physically correct (for example, say, obeys gravitational laws), unless explicitly intended otherwise, and also conforms to the animator's goals. These goals depend on the story sequence being narrated through the animated object. If the object being animated is an autonomous character (representative of a living creature that can generate its own forces to bring about its movement) then the resulting motion should not only be physically correct, but also appear realistic and natural. A walk should look like a walk and be different from a hop or a run.

Typically the autonomous character is modelled as an articulated body composed of links that are connected to each other via joints. These joints have associated actuators that generate all the internal torques which along with external forces like gravity, reaction, friction etc. are used by living creatures to bring about the desired motion. While in real life the limbs are usually flexible, for simplicity, in most computer simulations the links are considered as being rigid.

Movement or motion is a dynamic phenomena – it involves change in shape and spatial configuration of an object over time. Most often, in digital simulations the shape of an object is defined geometrically. Shape being such a fundamental attribute of physical objects in the world, it has been researched extensively and the field of geometric modelling and design has evolved almost as an independent discipline [76]. If the shape of the object surface changes over time due to effects of say, forces, then these are referred to as deformable bodies, otherwise as rigid bodies.

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1. More specifically, moves in accordance with Newton's laws of motion
2. The forces being applied are as they would be in a real world situation
3. Appears similar to the same type of movement performed in nature by an actual living creature of the same kind.
While there is considerable ongoing research on deformable objects [96, 73], our research is primarily concerned with the movement of rigid bodies linked together, referred to as articulated bodies, and which deform only by changing the joint angles.

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 or 30 frames (images) per second are shown. Animation is primarily concerned with motion synthesis, which is the creation/presentation of these images at discrete times. Strictly speaking therefore it 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. This function is then appropriately sampled in order to generate the individual frames showing spatial configurations of the creature(s).

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 $(x_v, y_v, z_v)$ and its orientation $(\theta_x, \theta_y, \theta_z)$ in three dimensional space. Degrees of Freedom (DoFs) constitute the minimal set of parameters needed to completely specify the configuration of a body in space. Degrees of Freedom are also known as generalized coordinates. Thus the spatial configuration of the pen in 3D has 6 DoFs. With just 6 parameters, the pen can be moved to any desired point and oriented in any desired direction in space. Depending on the number of links, joint types etc., an articulated body would have many more DoFs. Consider for example the planar articulated body with 3 links and 2 rotary joints as shown in Figure 1.1. This simple body has 5 degrees of freedom. Human bodies are amongst the most complicated of articulated bodies, with about 200 degrees of freedom [110]. A universally accepted convention is to consider degrees of freedom as constituting a vector and to 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 $X(t)$, $0 \leq t \leq T$. This is also referred to as the trajectory.
A simple definition of the motion synthesis problem is thus 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 pushed from a table of 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. and the initial force applied. Animators take years before they acquire the necessary skills to predict the spatial configuration of objects at any time instance for generating a specific movement. For living creatures, which bring about their own motion through internally generated forces and interaction with environmental objects like the wall or the ground, the motion synthesis problem becomes orders of magnitude more complex. It is only in very recent times with easy availability of computing power that motion synthesis tasks of such complexity are being undertaken [54].
There is another view to the motion synthesis problem. All possible motion paths for a given character can be considered as forming a space of trajectories. And the problem of synthesizing a particular motion can be viewed as that of searching for a suitable trajectory in that space. The trajectory that is finally selected must satisfy all the physical requirements and also the animator's goals. Consider the example of synthesizing the trajectory of the pen pushed from the table. (cf Figure 1.2.) From the space of trajectories that specific trajectory has to be chosen which accelerates as determined by the initial force and also by the gravitational force acting on it. Search for this kind of trajectory is comparatively simple and can be totally automated using what are being called as physically based animation techniques [10]. For autonomous articulated figures however, the search problem gets extremely complex. Firstly the number of DoFs is very large. As a result the trajectory space is of very large dimension. Secondly, there is always built in task level redundancy, i.e any behavioural goal can be achieved in many different ways. Thus, for example, a cup of coffee might be reached while moving the hand along many different paths. Usually the search is cast as a non-linear constrained optimization problem. The physical laws, and physical and user specified constraints are to be satisfied while the animator's goals are in the form of an objective function that has to be optimized.

Whatever may be the view, whether it is one of defining or creating a suitable trajectory or that of searching for the most suitable trajectory, the problem of synthesizing the movement of a virtual object or creature inhabiting and interacting with a virtual world consisting of other virtual objects or creatures remains the fundamental problem of computer animation. All research in computer animation is thus oriented towards new techniques that will enable
the development of software tools that will assist the animator in synthesizing different movements for different types of objects/creatures. Over the years a variety of techniques have evolved, ranging from providing the animator with simple tools for interactive drafting, painting and trajectory interpolation to the very highly sophisticated tools, that enable embedding of complex motion behaviour into the virtual object or creature. The focus has completely shifted from simple transformation based movements of single or groups of objects [78] to the complex movement of legged creatures [33, 87].

While in chapter 2 we shall present a more detailed and comprehensive review of the current state of the art in motion synthesis for articulated figures, below, we briefly describe a number of other disciplines in which motion synthesis is of concern.

Robotics

The construction of autonomous legged robots is one of the goals of robotics. This involves creating systems that can sense their environment and can travel in an obstacle filled environment. The two central issues that are of importance in robotics are that of motion planning and motion control. Motion planning [66] is typically treated as a geometric problem of obstacle avoidance whereas motion control [14, 86, 68] involves design of a control system.

Biomechanics

Biomechanics is the study of the mechanical bases of biological activity [106, 107]. One of the primary goals of biomechanics is to understand the mechanisms in human locomotion so that it is possible to have a better design of prosthesis for disabled persons. In this and other areas dealing with human limbs and their substitutes, a consensus is that the end (artificial) products should duplicate the performance of their biological counter parts as closely as possible.
Artificial life

In Artificial life, the goal is to mimic the behaviour of living systems in silico [62, 104]. Instead of trying to simply duplicate 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 logical rules behind that behaviour. Many of the simulated creatures are defined by compact code, which subsequently determines the creatures behaviour when placed in an environment. Most creatures being experimented with are still too simple.

Mechanical Simulations

For years, dynamic analysis [82, 42] programs such as DADS and ADAMS have incorporated graphical post-processors capable of displaying the motion of simplified models. The major benefit of such programs is that they allow the designer to quickly build an electronic prototype and test it to see how the moving parts will function in the real physical world. The recent work by Hodgins et. al [49] is one similar such application. They have applied dynamic simulation to a platform diver to study how changes in technique can affect the diver’s performance. Through motion simulation they could visualize what a dive might have looked like if the athlete had opened up earlier or later, or had left the diving platform differently.

1.2 A Relative Comparison of Motion Synthesis Studies

As can be seen from the brief descriptions of the different disciplines above, it is clear that motion synthesis is also a problem of interest in disciplines other than computer animation. While there are similarities in the studies, there are some fundamental and major differences in problem scope, research traditions and practical requirements. We elaborate on this in detail below.
Motion synthesis in artificial life is the closest to that in computer animation. In both areas virtual creatures have to interact and move in virtual worlds. However the emphasis in artificial life is on embedding mechanisms that enable learning of locomotion behaviour, and this along with all other kinds of performance behaviours. As of today, in this field movement goals are simple and are essentially self determined by the virtual creatures rather than imposed externally as done by animator. Real-time movement and response to collisions in the environment are additional constraints that make it very difficult at this stage to consider the embedding of highly complex external goal oriented motion behaviour. In the present state of art, the kinds of movements being synthesized are extremely simple as compared to what is desired for animated creatures. Moreover there is no requirement that the movements of these artificial creatures must appear realistic or natural.

Mechanical simulations, Biomechanics and Robotics are all concerned with the motion of real physical objects. Mechanical simulations deal with the motion of rigid linkages primarily towards understanding/analyzing their motion behaviour under different load conditions. There is certainly no explicit concern in any way to have these linkages represent, the limb structures of living creatures, though there have been some specific efforts towards simulating very specific movements like walking, hopping and diving. Biomechanics, while it is concerned with the motion behaviour of living creatures, is really concerned primarily at the individual limb and muscle level.

Motion planning and control in robotics once again comes rather close to motion synthesis in computer animation. There are however significant differences. In particular

1. The robot's linkage structure is physically real and it inhabits, interacts and moves in a real world. Unlike in computer animation, no idealized simplification is possible either for the parts of the robot or for the objects in the environment. Actuator forces, external interactions like collision and external forces like gravity, friction, reaction etc. are all real. As such, robots inhabit a very much more complex world than their virtual
countparts in computer animation.

2. On the other hand physical correctness is built in. A robot will not move through a wall, nor can its motion trajectories be not in accordance with the laws of physics. As such classical motion planning in robotics eschews physics totally. Since physical realisability of the synthesized motion is usually not of concern, the emphasis in robot motion synthesis is on obstacle avoidance, treated more as a geometric problem. Such an approach is clearly not appropriate for motion synthesis in computer animation.

3. An animated sequence may involve several characters with novel physical characteristics. Thus an animator would need to rapidly synthesize a variety of complex motions for one character and for many characters with different physical attributes. Whereas current studies in robotics are primarily concerned with a single robot or a class of robots with similar physical attributes.

4. An autonomous robot must be able to synthesize its motion trajectory independently. This is especially challenging in obstacle filled environments. In contrast an animator can afford to build up a character's motion trajectory piecemeal, concatenating a sequence of trajectories to obtain a final complex motion that avoids obstacles and behaves in conformance with the interaction with objects in the virtual world. Basically the animator and the computer can carry out the motion synthesis task in a collaborative manner.

5. Finally, in robotics real-time response is essential, and this puts very heavy demands on the computational resources that have to be built in. On the other hand in computer animation the synthesized motion is played back and has only to appear physically correct, realistic and natural. Computations taking time of the order of a few hours or days for synthesizing the motion of a few seconds are quite acceptable. There are no inherent demands on the kind of computing power that needs to be available. Also while physical correctness is a goal, appearance is more important and slight deviations not noticeable to humans can easily be permitted.
1.3 The Physical Basis in Motion Synthesis

Initial computer animation research can be dated back to early 1960's. The approach was purely geometric in nature. The responsibility lay entirely with the animator for the resulting motion to look physically correct, realistic and natural. The demands of physically correct behaviour had to be understood and imposed explicitly by the animator. Interactive tools were made available to assist in this task so that the animator could rapidly alter the synthesized motion at a local or global level and rapidly make the necessary number of trials before choosing the final trajectory for the object or character. By the late 1980's however, 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 and thus physically based animation was introduced. 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. Interaction with other objects in the environment and resulting behaviour is also modelled and a variety of collision detection and collision response techniques have evolved [53]. The idea is to incorporate appropriate physical complexity and realistic behaviour into the model itself, rather than imposing it on the animator. Initial results on incorporation of physics to produce realistic movements were very encouraging [3, 105, 52].

However, this is not without problems. As we shall see later in chapter 2, the specification of forces and torques to produce any desired motion is non-intuitive and certainly non-trivial. Further, once time varying forces and torques are specified, the motion is completely determined and is autonomous, and not any more under the control of the animator. Thus incorporation of physics into the model results into loss of fine control that an animator always needs to have over the generated motion. A number of techniques have therefore evolved to accept control specifications for desired motion in a more indirect manner but with adequate automatic methods built in for deriving the forces and torques that need to be applied [108, 100, 81, 38].
Thus in physically based animation today, the task of synthesizing motion is accomplished in several steps. These are listed below.

1. 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.

2. Supply physical parameters which include, mass, centre of mass and moment of inertia for each link.

3. Define control parameters that will enable automatic determination of necessary forces and torques which will bring about the desired motion.

4. Assemble the equations of motion and solve them using numerical techniques to obtain the position of the object over time.

5. Render the individual images (frames).

Of the five steps, except for the third, all others are very well studied and excellent working solutions exists [22, 29]. Step 3 however poses rather difficult problems.

Currently available methods trade off manual work for controllability versus autonomy for physical correctness. For example, there are methods to control at a low-level by interpolation of poses with adherence to physical constraints [15, 108]. There are also methods that expect only high level goal specification such as "Jump as high as possible" or "Walk as fast as possible" [81, 100]. Most of these problems are highly under constrained and use some kind of optimization in order to find a solution. Here, a critical problem lies in the specification of the performance metric. Performance metrics are very indirect ways of specifying motions and lack any immediate intuitive associations with the desired motions.

Typical performance metrics used are like minimization of external energy, or travel maximum distance etc. To associate such metrics with desired motions such as walk, jump, hop etc. is not very straight forward and involves lot of trial and error. As a result, physically based animation is still in the research
laboratories. Animators find it more convenient to use purely geometry based
techniques taking full responsibility for physical correctness and realism, while
keeping precise control over the synthesized motion. This is of course at the ex-
 pense of the considerable manual efforts that the animator has to put in. What
is really needed are high level physically based motion synthesis techniques
that require specifications which are easy, highly intuitive and at the same
time enable the animator to have any desired level of control over the gener-
ated motion. In short, more the automation the better it is, provided complete
control is in the hands of the animator. This research has primarily addressed
this problem and has proposed an innovative and implementable methodology
based on the use of motion features.

1.4 Thesis Statement

The different types of movements that we see in the real world have their
own distinct attributes or features that uniquely characterize them. A run is
different from a walk; which is different from a jump. For example in a walk
at least one foot is always on the ground at any time; where as in a jump
both feet can be away from the ground. Similarly its duty cycle, maximum
height from the ground and so many other attributes are different from that
of a jump. We refer to these distinguishing attributes as motion features.
Clearly, we humans are capable of recognizing motion features that enable us
to distinguish amongst different types of movements.

Mathematically speaking we represent a motion by the use of a feature vector
\( f = (f_1, f_2, \ldots, f_n) \), where \( f_1, f_2, \ldots, f_n \) are the \( n \) individual features. Each fea-
ture is a computable function which when applied to the given motion returns
a numerical value(s). Thus for a given motion \( X(t) \), \( f_i(X(t)), 0 \leq t \leq T \) denotes
the \( i \)th feature value. The set of motion features forms a feature space. In
feature space, motions of the same kind and for the same body cluster together.
Different kinds of motion result in different clusters and these clusters are
separable.
Our main thesis can now be stated as follows:

Motion features are quantifiable attributes of different types of movements and enable distinguishing amongst them. The task of motion synthesis of active articulated bodies for computer animation is specified in the form of a 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 global search procedures.

As part of this research a fairly elaborate implementation has been carried out to substantiate the above thesis. Using this implementation we have carried out the automatic synthesis of motion for planar articulated bodies by specifying desirable feature values for a predefined set of motion features. The automatically synthesized motion is played back in real time on the computer display screen. Our implementation simulates the motion for a given set of control parameters and uses the desired feature values to analytically formulate the fitness function that is used by an evolutionary programming algorithm to search for the desired motion.

Since the entire process is very demanding on computer time, the search process has been parallelized to run on a network of CPUs resulting in considerably reduced elapsed times for searching. The synthesized movements appear highly realistic and natural and the overall performance is extremely encouraging.

1.5 Thesis Organization

Chapter 2 is a comprehensive review of 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 movement 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.

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 or limitations, future extensions possible and some open problems in this area.