1. INTRODUCTION

Computer animation has long been an integral part of the simulation, motion picture, television and consumer entertainment industries and promises to play a much greater role in the future. As it becomes more pervasive, improved techniques will be needed to simplify and speed up the process of creating convincing, high quality animations. One key area of interest is the generation of motion for various types of creatures and characters to be used in an animation. These creatures are the actors of the computer graphics world. The way they move and interact with their environment has a great effect on a viewer's perception of the animation, whether it appears intentionally cartoon-like, or as an integral part of a realistic scene. In the quest for tools to generate realistic motion, one of the key directions of research has been the use of physically-based animation. This thesis presents an approach to the generation of bipedal locomotion for computer animations using physics-based simulations.

There are essentially two basic models used in the generation of motion for the purpose of animating articulated figures: kinematic models and dynamic models. The following brief overview of these approaches is useful for placing the research topic of this thesis in an appropriate context.

1.1 Kinematic Approaches

The most straightforward method for character animation is *kinematic* in nature. Kinematic animation is concerned only with the specification of joint angles and angular velocities over time. It does not deal with the forces and torques acting on or within a creature or their effect on the creature's motion.

Motion capture is a special case of the kinematic approach in which the joint angles and/or velocity data are measured from a real motion and then re-used on an animated character. The most common way of capturing a motion at present is to attach a series of markers to various points on the subject's body and to use multiple video cameras or other sensory devices to record the motion of the markers. The subject's motions are mapped directly onto the animated character, thereby ensuring that the animated motion will be realistic. The ability to modify, blend and transition between pre-recorded motions is important to provide the animator with sufficient control over the final motion. However, results based on modifications of captured motions are not guaranteed to remain realistic.

1.2 Dynamics

An alternate approach toward providing realism is the use of physically-based animation. In this scheme, motions are the result of physical simulations, which include detailed modeling of internal and external forces and torques, the creature's mass and moments of inertia, and its interaction with the environment. All these parameters affect the final result, as they would in the real world. The essence of this approach is to ensure realism by constraining the motion of the system to abide by the laws of physics. Dynamics-based animation has the advantage that the task of ensuring that motion is physically realistic has been automated. The animator is, in principle, free to apply his or her abilities to the more artistic aspects of the animation process. Note that "realism" in this context refers to behaviour consistent with a simulated model of the real world. Similarity to the real world depends completely on the fidelity of this model.

This approach introduces new and challenging problems to be solved in order to be of practical use. First, incorporating dynamics effects involves the integration of the equations of motion over time, and has historically been computationally expensive for all but the most simplistic problems. While it seems that no amount of computing power is truly enough, efficient simulation algorithms and faster hardware are beginning to bring the simulation of complex systems of interest to animators into the realm of real-time performance. A second problem, which remains largely unsolved, is often called the *control problem* of dynamic animation. Briefly stated, in the context of computer animation, the control problem is:

> Given a creature, an environment and a desired motion specified by the animator, what are the control forces and torques required to achieve the desired motion or a close, physically-realistic approximation?

While the incorporation of dynamics in the generation of computer animations has been a topic of significant research interest for approximately a decade [AG85] [WB85] [Wil86], it is only now beginning to play a more serious role in commercial computer animation systems. A dynamics simulator is now a part of one of the most popular computer animation packages [Alias]. The delay is due to both the performance issues and a lack of suitable solutions to the control problem.

This thesis provides an approach to solving the control problem for bipedal locomotion.

1.3 Goals

The primary goal of this thesis is to provide a technique for the animation of physically-based bipedal locomotion. More specifically, we present a control solution for articulated figures performing cyclic motions such as walking. Aperiodic motions such as sitting down and standing up are not addressed.

Within this context, this thesis has a number of more specific objectives:

- The technique should work for statically unstable articulated figures. This means that it must provide some form of ongoing corrective control actions.
- The basic approach should be general in nature, allowing for a wide variety of periodic motions without changes to the basic control structure.

- The approach should work for creatures of reasonable complexity without making any fundamental assumptions about the creature's structure. In particular, it should at least be suitable for animating a human model with tens of degrees of freedom (DOFs).
- The control representation should be relatively compact, and flexible enough to allow straightforward specification of walking variations.
- If desired, the motion should exhibit autonomy. For example, the animator might be allowed to specify the start and end points of a walk rather than being required to specify the placement of the foot for each step.

Two desirable objectives which we do not directly address are "naturalness" of the resulting motion (as opposed to physical realism) and interactivity. While both of these features are important to have in an animation system, the problem of generating bipedal locomotion subject to the above goals is a sufficiently challenging intermediate goal. Nevertheless, the proposed technique affords the animator the freedom to potentially obtain natural looking motions with reasonable additional effort compared to generating basic course motions. As well, expected increases in computer performance over the next year or two promise to make interactive use of the system a realizable goal.

1.4 Thesis Organization

This thesis is divided into 6 chapters. Chapter 2 summarizes the previous related work and presents the background material necessary to understand the chapters which follow. It also provides an overview of our animation system. Chapter 3 discusses the underlying principle of our control approach. It further describes the general control structure and its application to the generation of balanced, cyclic locomotion. Chapter 4 presents the basic results of applying the control formulation to bipedal walking. Chapter 5 describes further results for variations on walking gaits. The ability to have the walking biped follow a desired path is also demonstrated. Finally, Chapter 6 concludes the thesis and discusses a number of possible directions for future work.