LITERATURE REVIEW

Chapter – 2

LITERATURE REVIEW

2.1 INTRODUCTION

Walking is the most common means of moving about and is one of the essential activities of our daily life. Other locomotion methods such as running, hopping and jumping, all have common patterns of movement, and by studying walking, it becomes easier to understand the rest. Human walking can be described as a smooth, highly coordinated, rhythmical movement by which the body moves step by step in the marching direction. It requires the simultaneous involvement of all lower limb joints in a complex pattern of movement. This chapter reviews on the dynamic motion planning for human walking and the influence of dynamic parameters on the walking mechanism.

2.2 KINEMATICS APPROACHES

Kinematics approaches produce motions from positions, velocities, and accelerations, that is, all the geometrical and time-related properties of the motion. Kinematics of robot is the study of motion independent of the forces, which cause it. Any robot can be described kinematically by giving the values of four quantities for each link. These quantities are called the Denavit – Hartenberg parameters [21]. Kinematics approaches for simulating human locomotion have been described by several researchers over the years [22- 26]. These approaches generally fall into one of the two categories:

- Forward kinematics
- Inverse kinematics

2.2.1 Forward Kinematics

Forward kinematics approaches provide motion control by specifying the joint angles over time. The motion of the end-effector is determined as the accumulation of all transformations from the chain root to the end-effector. The major advantage of forward kinematics approaches over the other motion control techniques is that they provide the animator complete-control of the motions in minimal cost of computation. However, the animator will have to deal with the following difficulties:

- When applying forward kinematics directly, obvious constraints imposed on the motions may be violated. For example, in animating human locomotion, the most fundamental constraints are that the supporting foot should not go through or off the ground, and that the global motion should be continuous (especially at the heel lift-off and strike points). Special handling will be required to satisfy these constraints. One solution for this locomotion problem with forward kinematics is to switch the root of the hierarchical structure, based on the constraint situations (i.e. make the supporting foot the root).

- Although motions generated by this technique look convincingly real, the technique is quite labor-intensive and requires considerable talent in order to get the desired results. As the complexity of the articulation increases (i.e. a more complex human model or movement), the usage of this technique will become less practical.

Because of the complexity problem of human structure, much of the research in motion control has concentrated on providing the animator with high-level control, which will reduce the amount of specification necessary to achieve a desired motion. An early work by Zelter [27] used hierarchical motor control techniques to animate locomotion of a human skeleton with a straight-ahead gait over level, unobstructed terrain. Variations of walking, such as different walking styles or walking on moderately uneven terrain were achieved by parameterizing the generalized walk controller and its associated motor programs. Unfortunately, this requires the user the detailed knowledge of the skeleton animation system as well as programming experience. Another drawback of this approach is that the animator must trade artistic control in return for automatic motion synthesis.

Bruderlin and Calvert [28] proposed procedural animation techniques to animate personalized human locomotion. In their system, three locomotion parameters, step length, step frequency and velocity were used to specify the basic locomotion stride. Then, additional locomotion attributes were added at different levels of the motion control hierarchy to individualize the locomotion. The complexity of their control algorithm is simple enough to provide the animator interactive control of personalized human locomotion. Because their computation model is mainly based on normal walking on flat ground, its application is highly limited in virtual environments.

2.2.2 Inverse Kinematics

Inverse kinematics is adopted for end-effector goal positioning. It computes the joint angles for each segment in the chain structure from the position and orientation of the end of the limb. The advantages of inverse kinematic approaches over the other motion control techniques are:

- The animator defines the configuration of the end effector only, and inverse kinematics will solve for the configurations of all joints in the link hierarchy. In general, specifying only the motion of the end-effector is more intuitive and easier than explicitly specifying all joints for the animator. This also implies that the quality of the motion is highly depended on how well the body trajectories are defined.

- The constraint satisfaction such as the feet must stay at certain positions during locomotion can be precisely executed, using inverse kinematics. This constraint satisfaction characteristic makes inverse kinematic method a useful tool in dealing with constraints regarding end-effector configuration for most of the existing animation system.

Boulic et al. [22] used a generalization of experimental data based on the normalized velocity of walking. The generalization, in its direct application, could produce undesired results; such as parameters violate some of the kinematic constraints imposed on walking. Inverse kinematic was implemented to correct these problems. Among the multiple inverse kinematic solutions, the one that was the closest to the original motion was chosen to preserve the original characteristics of the walking data. Based on the Jack system [27], Phillips and Badler [29] implemented an inverse kinematics algorithm to generate motions. The users have to choose properly the end-effectors and then define sets of constraints that drive the limbs to move in desired patterns. Minimization of energy described by the constraints was used to choose the set of joint angles among the multiple inverse kinematics solutions. Koga et al [30] used a path planner to compute the collision-free trajectories for cooperating arms to manipulate a moveable object between two configurations. An inverse kinematic algorithm was utilized by the path planner for the generation of forearm and upper arm postures to match the hand position. Then, joint angle of the wrist was computed to match the hand orientation.

For systems that devote to human locomotion, Girard [31] used a mix of kinematics and "pseudo-dynamic" methods to simulate human locomotion. A multi-pass process was used to determine the body motion that could fit a set of footprints. The vertical body motion was computed by a fixed family of functions during support. The horizontal motion was computed independently using a velocity-error feedback loop. As the motion of the body was defined using the kinematic constraints and simple dynamics, the legs were animated kinematically using a pseudo-inverse Jacobian technique to make the leg angles close to the desired angles while keeping the foot on the ground during support. Using the above approaches, some of the most impressive human animations to date were produced.

2.3 DYNAMIC APPROACHES

Dynamic approaches describe motion by a set of forces and torques from which kinematic data is derived. Dynamic simulation and control algorithms [32–39] have been used to generate motions of articulated figures for years, and there is also a significant body of robotics research concerning the control of bipedal locomotion, as well as biomechanics for simulating human walking motions. However, to date physical-based modeling of human locomotion still presents one of the most challenging tasks in the computer animation community. This is probably because joint contact and individual muscle forces during gait are still not well known and the difficulties in modeling formulation and solution. The determination of limb center of mass and inertial properties add more complexities and uncertainty in the dynamic motion planning.

McKenna and Zeltzer [38] simulated the gait of a virtual insect by combining dynamic simulation and a walking algorithm that was based on the motion patterns observed in insect locomotion. Raibert and Hodgins [39] used a similar approach but a different motion controller. They fashioned the models from analyses of robots and real creatures. Numerical integration of the dynamic model and specific control algorithms were used to generate running and jumping motions of multi-legged imaginary creatures. Hodgins et al [34] introduced a dynamic approach to animate human running. The control algorithm was based on a cyclic state machine, which could determine the proper control actions to calculate the forces and torques. Hodgins and Pollard [35] further extended the work of Hodgins et al [34] to show that existing simulated motion could be adapted to new dynamic models while maintaining the important characteristics of original motion. Using their approaches, they were able to animate the running motion of a child, woman, and imaginary biped creature by modifying the control system for a man.

The results of McKenna & Zeltzer [38] and Raibert & Hodgins [39] proved that dynamic approaches with proper control algorithm could produce some very life-like and experimentally validated motions. However, the motions produced to date have been limited to relatively simple creatures performing simple locomotion. For autonomous locomotion on rough terrain or cluttered environment, a more robust model with intelligent control algorithm is required to achieve the animation goals.

2.4 HYBRID (KINEMATICS AND DYNAMIC) APPROACHES

Beyond kinematics methods, some hybrid locomotion techniques have been proposed to generate walking motions by adding physical properties. The task is to find effective combinations that generate realistic motion while providing animator reasonable and intuitive control over the motion. In general, simplified dynamic models are applied to simulate some parts of articulated figure, such as the swing leg, support leg, or the body as a whole. They are responsible for the enhancement of realistic part of the animation. Kinematics, on the other hand, gives animator the flexibility to control the desired motions. Several researchers [31, 40, 41] have implemented this technique in articulated figure animation.

Armstrong and Green [32] and Wilhelms [42] proposed similar methods where all of the links of the articulated figures were under control of the dynamic simulation, but the animator could constrain the motion through kinematic means. For each individual link in the structure, one of the four kinematic control strategies was assigned to constrain its movement. Then, the system would generate required forces that work to exactly match the kinematically defined motions. A similar technique was proposed by Westenhofer and Hahn [43]. Different from [32] and [42], dynamics was used to enhance kinematically created motion with realistic effects, instead of exactly matching it. The realism was highly depended on the kinematic specification. Westenhofer and Hahn's approach provided more flexibility in achieving natural continuous motion [43]. Bruderlin and Calvert [40] used a similar mix of techniques to generate parameterized walking motion. The concept of step symmetry was applied to find the end positions of the supporting hip. A telescoping leg model with two degrees of freedom was used to compute the trajectory of the supporting hip during step time. Rather than using a general dynamic model, the equations of motion were tailored to suit for only a specific range of movement and time period. Proper forces and torques that drive the dynamic model of the leg were then determined by numerical approximation techniques.

2.5 RELATED STUDIES IN BIOMECHANICS AND HUMAN GAIT ANALYSIS

Research in biomechanics and human gait analysis [44-51] has made extensive studies of human body motion during normal level walking. Principle results have come from careful analysis of motion patterns, such as configuration (both position and orientation) of body joints, muscles' activities (from electromyography), and reaction of the foot with the ground (force plate). They provide a rich resource for simulating human locomotion. However, most attention has been on level walking. To date published work that addresses non-level walking is rare. Beckett and Chang [52] made studies of the energy expended in walking by analysis of the motion of the leg and foot in the swing phase of a step. The energy consumed was obtained by evaluating the work done in traveling a given distance. It appears that the results check reasonably well with natural gait, and indicates that for a given individual there is a natural gait at which he can travel a given distance with minimum effort.

The model of energy minimization does not take into consideration the necessity of maintaining balance during gait. In Redfern and Schumann's work [53], they proposed a model of foot placement control that provides a stable base of support. Foot placements were chosen to minimize the sum, in terms of position and velocity with respect to the pelvis, of the supporting and swing feet. They conducted experiments to test the model during walking trials of different speeds. They concluded that the sum of the supporting and swing feet (positions relative to the pelvis) was very close to zero at heel contact.

Andriacchi et al. [54] studied the motions, forces, and moment at the major joints of the lower extremities in subjects going up and down stairs. Their work provided one of the most comprehensive sets of data on lower-limb mechanics in normal subjects during stair walking. The common patterns of motion, forces, and muscle activity of the lower limbs were described, and there was some useful information on the strategy changes in stair walking.

An analysis, which integrates kinematic and kinetic data of lower limbs in stair walking, was described by McFadyen and Winter [55]. They found that the strategies for climbing and descending stairs might vary. Most variability was seen at the hip. They also observed that a significant progression occured during 'pull-up' in early stance for ascent and 'landing' in late stance for descent. The knee extensors were responsible for the greatest generation of energy during these events. They concluded that the magnitude of the supporting moments for stair climbing was greater. From the animator's viewpoint, this observation might indicate the possibility of a generic motion control mechanism for all human stepping activities.

Townsend and Tsai [56] proposed a bipedal robot model for uneven terrain walking. Their approach used a common locomotion algorithm and varied the coefficients and initials to generate a certain range of gaits. The climbing and descending gaits were synthesized according to generalized postural stability and other feasibility requirements for a kinematically constrained, articulated walking model. Although their studies were for biped machine, instead of human, many of the practical constraints and conditions were derived from human motion characteristics or to be compatible with human motion. The results concluded that general characteristics could be identified with the swing leg take-off or touchdown conditions for a given gait algorithm. Thus, system kinematics was such that iteration or control could utilize the initial and last terminal configuration data to define subsequent walking. A variety of walking could be achieved by modifying the same basic gait algorithm and varying initial conditions.

2.6 HUMAN WALKING MODEL

Human walking requires the simultaneous involvement of all lower limb joints in a complex pattern of movement. Basically, all normal people walk in the same way. From human gait observations [48], the differences in gait between one person and another occur mainly in movements in the coronal and transverse planes. Throughout the whole body, those joint movements that occur in the sagittal plane are very similar between individuals, and if the upper limbs are unencumbered, they actually demonstrate a stereotyped pattern of reciprocal movement in phase with the lower limbs.

2.6.1 Terminology of gait

Human walking is a complex activity, and, for the purpose of computer simulation, human gait is required to analyze and to break down into temporal and spatial components.

Some of the following terminology of gait relates to the period of time during which events take place, and some refer to the positions or distances covered by the limbs.

Gait cycle: The *gait cycle* is defined as the time interval between two successive occurrences of one of the repetitive events of walking. Although any event could be chosen to define the gait cycle, it is usually convenient to use the instant at which the heel of one foot strikes the floor as the beginning, and the moment when the same heel strikes the floor again as the ending of the gait cycle. Based on the events during the gait cycle, it can be subdivided into support, swing, and double support phases, which describe the periods of time when the foot is either in contact with the floor, or swinging forward in preparation for the next step. These phases and their timings are illustrated in Figure2.1.

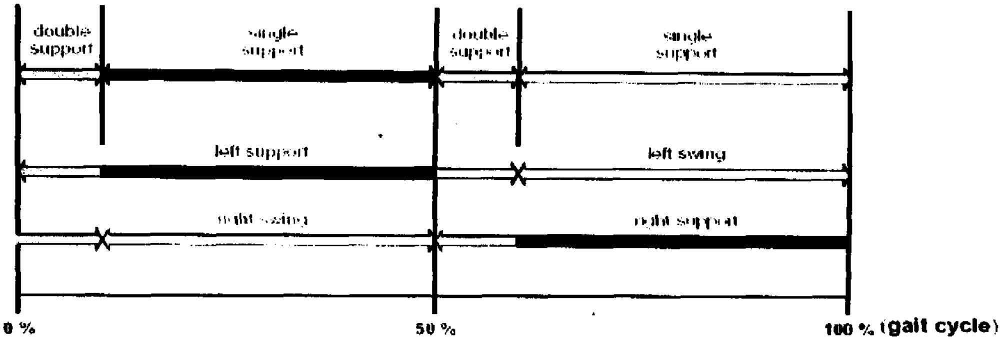

Figure 2.1 Gait cycle of human walking

Support phase: The support phase is the period of time when the limb under consideration is in contact with the floor. It provides the stability of the gait, and is necessary if an accurate swing phase is to take place. Based on the spatial relationship between the supporting foot and the floor, the support phase can be further subdivided into the following stages.

Heel strike: This is the first moment of foot-floor contact for the leading limb. At the moment of heel strike the following limb is also in contact with the floor, giving a phase of double support. In normal walking, this is the moment that the center-of-mass of the body is at its lowest, and the walker is most stable.

Mid-stance: This is the period that the supporting foot is flat in relation to the floor. In mid-stance, the body is carried forward over the supporting limb, and the opposite limb is in the swing phase. The whole body center-of-mass passes from behind to in front of the supporting foot during this phase. It rises to its highest position in relation to the floor at about the middle of this period. This is also the position where the walker is least stable.

Push off: This period starts from the end of 'flat foot' and ends at the end of support phase. Initially, there is 'heel off', followed by a propulsive stage that is called 'push off' which leads to the moment of 'toe off' when propulsion ends and the swing phase starts.

Swing phase: During the swing phase, the swing limb moves in front of the supporting limb so that forward progression can take place. This phase can be subdivided into three stages.

Acceleration: The driving forces come from the hip (major) extensors and plantar (minor) flexors. The non-weight-bearing limb is accelerated forward in this period.

Mid-swing: This corresponds with mid-stance. At this moment the swing limb passes the supporting limb with rather steady speed.

Propulsive breaking: In this final stage of the swing phase, the lower limb muscles work to decelerate the swing limb in preparation for heel strike. The activities of the muscles in this stage are usually eccentric and need less energy than phases of the gait cycle when concentric activity is required to accelerate a limb.

Double support phase: The double support phase is the period of time when both feet are in contact with the ground. It is a small interval during the gait cycle when two leg events are overlapped: the final fraction of the support phase from one leg, and the beginning fraction from the other leg. Its temporal length is equal to the difference between the support phase and the swing phase. On normal walking, this also is the period of time where the body travels through its lowest vertical height during the gait cycle.

Duty factor: Leg duty factor describes the time a foot stays on the ground as a fraction of the gait cycle. For bipedal gait, this can be used to distinguish between walking and running. If the leg duty factor exceeds 0.5, the figure is in walking mode, and if it is less than 0.5, the figure is in a running state. Human gait observations have shown that during average speed of normal walking, the support phase takes about 60% of the time of the gait cycle and the swing phase about 40%. This means that average normal walk has a leg duty factor of about 0.6. The double support phase and leg duty factor can be computed as follows:

Step duration = Support duration + Swing duration

Duty factor = Support duration / Step duration

Double support duration = (Support duration - Swing duration) / 2

2.7 SUMMARY

The available literature was reviewed:

- To identify the technological gaps among the strategies and technologies applied to walking mechanism.
- To formulate the strategic and logical approach with the parameters and approaches considered for the present work.

A new approach has been developed to estimate the mass, location of center of mass, moments of inertia of each link and the friction at each joint of a robot during manipulator movement. These dynamic parameters are factorized linearly using the geometric operators of Lie groups and Lie algebras. The Lie group formulations have been derived based on hybrid dynamics. The Lie group formulation of inverse dynamics is rearranged in a linear matrix form of the dynamic properties. The least square method has been employed to identify the dynamic properties after exciting the robot and collecting the data of joint positions, velocities, accelerations and applied forces.