HUMAN MOTION CONTROL USING INVERSE KINEMATICS

A THESIS

SUBMITTED TO THE DEPARTMENT OF COMPUTER ENGINEERING

AND THE INSTITUTE OF ENGINEERING AND SCIENCE

OF BILKENT UNIVERSITY

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF

MASTER OF SCIENCE

By

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August, 2003

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ABSTRACT

HUMAN MOTION CONTROL USING INVERSE KINEMATICS

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Articulated figure animation receives particular attention of the computer graphics society. The techniques for animation of articulated figures range from simple interpolation between keyframes methods to motion-capture techniques. One of these techniques, inverse kinematics, which is adopted from robotics, provides the animator the ability to specify a large quantity of motion parameters that results with realistic animations. This study presents an interactive hierarchical motion control system used for the animation of human figure locomotion. We aimed to develop an articulated figure animation system that creates movements , like goal-directed motion and walking by using motion control techniques at different levels. Inverse Kinematics using Analytical Methods (IKAN) software, which was developed at the University of Pennsylvania, is utilized for controlling the motion of the articulated body using inverse kinematics.

Keywords: kinematics, inverse kinematics, articulated figure, motion control, spline, gait.

ÖZET

TERS KİNEMATİK YÖNTEMİ KULLANILARAK İNSAN HAREKETİNİN KONTROLÜ

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Eklemli vücutların animasyonu bilgisayar grafiği alanında en fazla ilgi çeken konulardan biridir. Eklemli vücutların animasyonu için geliştirilen teknikler, anahtar resimler arasında ara değer kestirimi metodlarından hareket yakalama tekniklerine kadar geniş bir yelpaze oluşturmaktadır. Bu tekniklerden biri olan ve robotbilimden uyarlanan ters kinematik yöntemi, canlandırıcıya birçok hareket parametresini tanımlayabilme imkanı vererek gerçekçi bir animasyona olanak sağlamaktadır. Bu çalışmada, insan vücudunun yürüme hareketi için kullanılan etkileşimli, hiyerarşik bir hareket kontrol sistemi anlatılmaktadır. Ayrıca, çalışma kapsamında, hedefe yönelik hareket ve yürüme gibi değişik seviyelerde hareket kontrol teknikleri kullanılarak, eklemli vücut canlandırması yapan bir sistem geliştirilmiştir. Eklemli vücudun hareketini ters kinematik yöntemi kullanarak kontrol etmek için, Pennsylvania Üniversitesi'nde geliştirilen IKAN yazılım paketinden yararlanılmıştır.

Anahtar kelimeler: kinematik, ters kinematik, eklemli vücut, hareket kontrolü, eğri, yürüyüş.

ACKNOWLEDGMENTS

I am gratefully thankful to my supervisors Prof. Dr. Bülent Özgüç and Assist. Prof. Dr. Uğur Güdükbay for their supervision, guidance, and suggestions throughout the development of this thesis.

I would also like to give special thanks to my thesis committee member Prof. Dr. Özgür Ulusoy for his valuable comments.

I would also like to thank Şahin Yeşil for his invaluable support.

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To my family...

Chapter 1

INTRODUCTION

Today, computer graphics has reached to a point where computer generated images has become almost indistinguishable from the real scenes. Nevertheless, animating the objects in a realistic manner is still difficult, particularly as object models become more complex. As a result, the specification and control of motion for computer animation became one of the principal areas of research within computer graphics community.

One area, which receives particular attention, is figure animation. Research in this area focuses on generating realistic articulated figures, and designing and controlling their movements. There are many applications in which virtual humans are involved; from special effects in film industry to virtual reality and video games. However, the human motion created by the artists is not always realistic and the reasons that prevent the realism increase the difficulty of the task.

During fifteen years period in the study of human motion, many techniques based on *kinematics, dynamics, biomechanics,* and *robotics* was developed by the researchers. The task was very complicated but the interest for this area has never decreased. It was used in several applications, such as robotics, art, entertainment, education, and biomedical researches and the type of application in which walking motions is used, determined the constraints that the model has to solve. On the one hand, video games or virtual reality applications require the minimization of the ratio between the computation cost and capabilities of the model. However, for biomedical researches, the important constraint is that the model must be realistic and the animation of the model should obey the physical laws. Therefore, the models are designed and animated according to the specific application area in which they are applied. It is possible to classify the animation of the models into three main groups:

- *procedural methods* based on kinematic animation,
- *dynamic methods* based on dynamics constraints, and
- *motion capture* methods.

In this study, we aimed to develop an articulated figure animation system that creates movements using low-level motion control techniques, goal-oriented animation, and high-level motion control techniques like walking. *Inverse kinematic* techniques were used mainly for creating new movements.

The articulated figure is modelled using Extensible Markup Language (XML) data format. The hierarchy of joints and segments of human skeleton and their naming conventions are adopted from the Humanoid Animation (H-Anim) 1.1 Specification. Besides, the elements of the XML data is organized as they are corresponding to the nodes of the H-Anim structure. However, since the whole hierarchy defined in H-Anim 1.1 Specification is redundant for our system, a simplified version of the hierarchy is implemented. The resulting framework is suitable for modeling various articulated structures like humans, robots and etc.

This study solves the motion controlling of the articulated figure by a low-level control of motion using kinematic methods. We characterized this low-level motion control by using spline-driven animation techniques. Besides, a high-level walking system, which is based on low-level techniques, is introduced.

Smooth motions are generated using spline-driven animation techniques. A class of cubic splines, Cardinal splines, is preferred due to their less calculation and memory requirements and capability for local control over the shape. Cardinal splines are used in generating the paths for pelvis, ankle, and wrist motions, which are considered as position curves. In addition, a velocity curve or distance curve for each object is produced that enables us changing the behavior of the motion. Arclength parameterization of the spline method is used in order to determine the position of each object along the position curve at each frame. All of these are the components of our low-level animation system.

By using this low-level system, a high-level motion mechanism for walking is implemented. In walking motion, the limb trajectories and joint angles are computed automatically using some parameters like locomotion velocity, size of walking step, the time elapsed during double-support, rotation, tilt, and lateral displacement of pelvis.

Inverse kinematics is heavily used in our system. *Inverse Kinematics using Analytical Methods (IKAN)* software package, which was developed at the University of Pennsylvania, is used to compute the desired limb positions.

1.1 Organization of the Thesis

The thesis is organized as follows: Chapter 2 reviews computer animation techniques and discusses their applicability in the articulated figure animation. In Chapter 3, the articulated figure modeling approach that is used in our study is discussed. Chapter 4 focuses on low-level and high-level motion control techniques in our system. Chapter 5 deals with the capabilities of IKAN software, and the usage of this tool in our study. Chapter 6 gives the performance results of the implementation. Chapter 7 presents conclusions and future research areas. In Appendix A, the human model in XML format that is used in our system is described. Appendix B focuses on class diagrams and implementation details. Lastly, Appendix C gives information about the application and its user interface.

Chapter 2

RELATED WORK

This chapter summarizes the computer animation techniques for articulated figure animation in general. It depicts the human figure modeling techniques and the advantages and disadvantages of basic motion control techniques for figure animation. Moreover, a summary is given about the background work in human walking.

The work involved in the animation of human motion, could simply be divided into three major steps: *modeling the basic structure (skeleton)*, *motion of the skeleton*, and *creation of the body appearance.* In this chapter, related work including the figure modeling and control of the motion of the skeleton will be given.

2.1 Body Models

One of the main problem in human character animation is the model structure. What kind of model we will use. It is clear that building a physically realistic model as possible as a real human character is the main goal. The ideal, computer generated character should consider the accurate positioning of human limbs during motion, the skin where muscles and tissue deforms during the movement, expressive facial expressions, realistic modeling of hair, and etc. However these are all research topics in their own right.

The basic approach to this problem is to start with structuring the skeleton part of human and then, adding the muscle, skin, hair and other layers to that structure. Skeleton layer, muscle layer, and skin layer are the most common ones. This *layered modeling technique* is heavily used in human modeling field of computer graphics [14]. In that approach, motion control techniques are just applied on the skeleton layer and this simplifies the challenging work because there is no need to think about the details of the model.

Modeling the articulated skeleton is the trivial part of the human body modeling. Skeleton can be represented as a collection of simple rigid objects connected together by joints. The joints are arranged in a hierarchical structure to model human like structures. These models, called articulated bodies, can be more or less complex. The number and the hierarchy of joints and limbs and the degrees of freedoms (DOF) of joints determine the complexity of model. Degree of freedom of a joint is the independent position variables that are necessary to specify the state of the joint (see Figure 2.1). The joints can rotate in one, two, or three orthogonal directions. The number of these orthogonal directions determines DOF of a joint. A human skeleton may have many DOFs. However, when the number of DOFs increases, the mathematics of the structure, which is used for controlling the joints, becomes more complex. Besides, some restrictions such as limiting the rotation angle of that in each of the rotation directions, provide more simplified solutions.

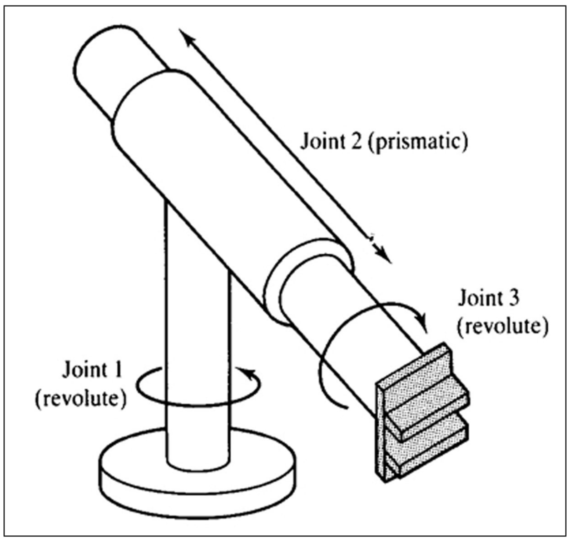


Figure 2.1: A manipulator with three degrees of freedom (reprinted from [41]).

2.1.1 The H-Anim 1.1 Specification

Modeling the basic structure of the articulated figure is the trivial part of the challenging work. However, a challenge arises when human model needs to be interchangeable. A standard should exist among the people who deal with human modeling, so that interchangeable humanoids can be created. The Humanoid Animation Working Group of Web3D Consortium developed the *Humanoid Animation (H-Anim)* specification for this purpose. They specified the way of defining humanoid forms and behaviors in standard Extensible 3D Graphics/Virtual Reality Modeling Language (X3D/VRML). In the scope of their flexibility goal, no assumptions are made about the types of application that will use humanoids. Their simplicity goal guided them to focus specifically on humanoids, instead of trying to deal with arbitrary articulated figures.

Human body consists of a number of *segments* (such as the forearm, hand, foot) that are connected to each other by *joints* (such as the elbow, wrist and ankle). The H-Anim structure contains a set of nodes to represent the human body. The nodes are `Joint, Segment, Site, Displacer,` and `Humanoid`.

`Joint` nodes represent the joints of human body and they are arranged in a strictly defined hierarchy. They may contain other `Joint` and `Segment` nodes. `Segment` nodes represent a portion of the body connected to a joint. They may contain `Site` and `Displacer` nodes. `Site` nodes are used for placing cloth and jewelry. Besides, `Site` nodes can be used as end-effectors for inverse kinematics applications. `Displacer` nodes are simply grouping nodes, allowing the programmer to identify a collection of vertices as belonging to a functional group for ease of manipulation. `Humanoid` node stores information about the model. It acts as a root node for the body hierarchy and stores all the references to `Joint,` `Segment,` and `Site` nodes. The basic structure of human body model is built by using these nodes in a H-Anim file. In addition, a H-Anim compliant human body is modeled "at rest" position. At that position, all the joint angles are zero and humanoid faces the +z direction, with +y being up and +x to the left of the humanoid according to right hand coordinate system. The complete body hierarchy with joints and their associated segments, and naming conventions for H-Anim Specification is given in Figure 2.2.

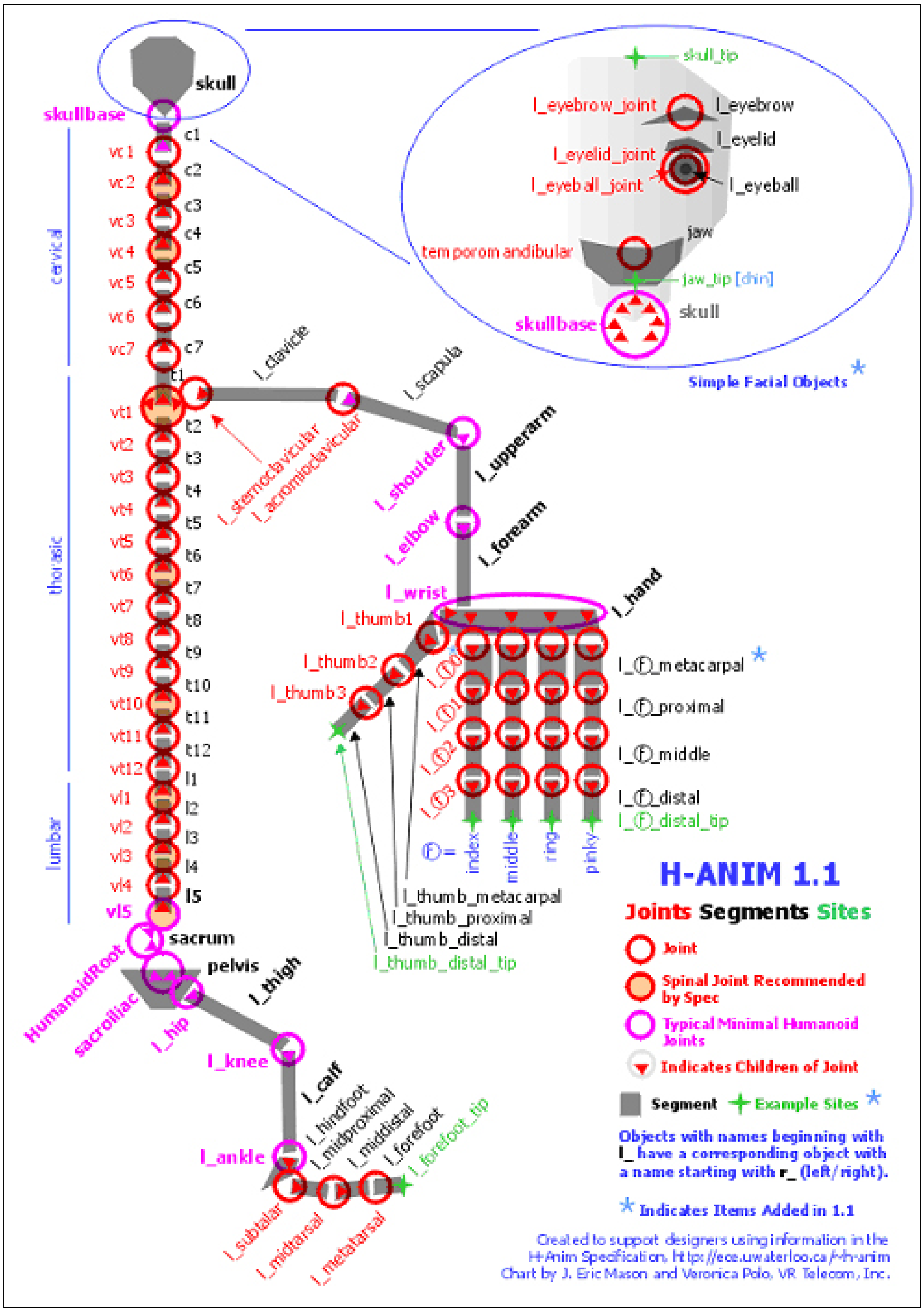


Figure 2.2: The H-Anim Specification 1.1 hierarchy (reproduced from [36]).

2.2 Kinematics

Kinematic methods, which originate from field of robotics, is one of the approaches used in motion specification and control. Animation of the skeleton can be performed by changing the orientations of joints by time. Motion control is the management of the transformations of the joints by time. Kinematics is the study of motion by considering the position, velocity, and acceleration. It does not emphasize on the underlying forces that produces the motion. *forward* and *inverse kinematics* are the two main categories of kinematic animation.

2.2.1 Forward Kinematics

Although articulated figures are constructed from a few number of segments, we should deal with much number of degrees of freedoms. There are many motion parameters that should be controlled to have the desired effect on a simple character. Forward kinematics is the way of setting the such motion parameters, like position and orientation of skeleton, at specific times. By directly setting the rotations at joints, and giving a global transformation to the root joint, different poses can be handled. The motion of the end-effector (in the case of arm, the hand) is determined by indirect manipulations of transformations in root joint of skeleton, and rotations at shoulder and elbow joints. Mathematically, forward kinematics is expressed as

$$x = f(\Theta) \tag{2.1}$$

That is, given Θ, derive x. In case of the leg, given the rotation angles of knee and hip, the position of the foot is calculated by using the positions and rotations of the hip and knee.

In order to work on the articulated figures, a matrix representation, which will define the rotation and orientations, should exist. Denavit and Hartenberg were the first who developed a notation, called *DH notation*, to represent the matrix formulation for kinematics of articulated chains [16]. DH notation is a link based notation where each link is represented by four parameters; Θ, d, a, and α (see Figure 2.3). For a link, Θ is the joint angle, d is the distance from the origin, a is the offset distance, and α is the offset angle. The relations between the links are represented by 4×4 matrices.

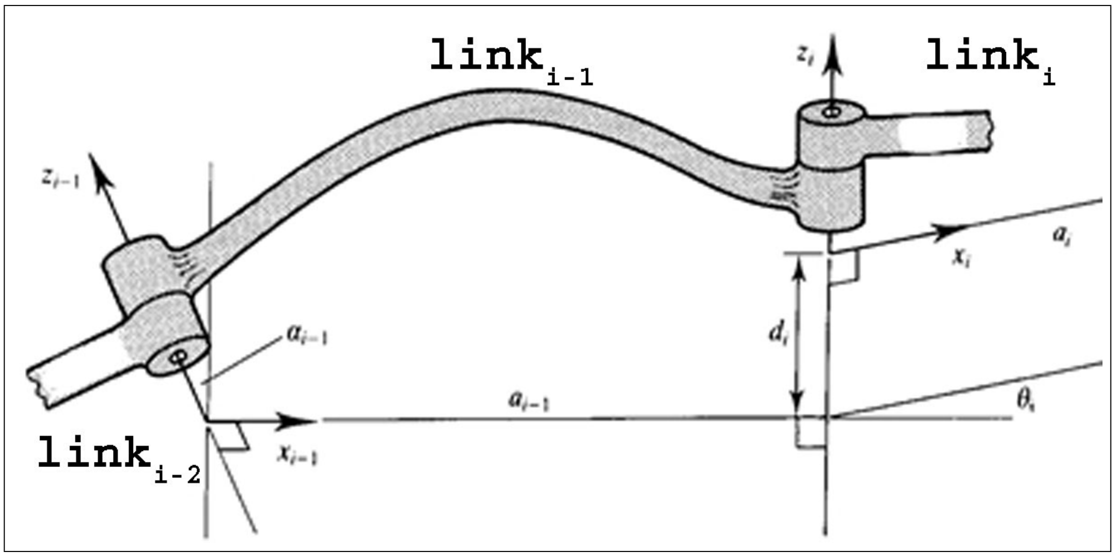


Figure 2.3: The Denavit-Hartenberg Notation (adopted from [16]).

Moreover, Sims and Zeltzer [35] proposed a more intuitive method, called *axis-position (AP) representation.* In this approach, the position of the joint, the orientation of the joint and the pointers to joint's child nodes are considered to represent the articulated figure.

In forward kinematics, after the orientation matrix of each joint is calculated, the final position of end-effector is found by multiplying the matrices in the same manner as computing graphics transformation hierarchies.

2.2.2 Inverse Kinematics

Inverse kinematics is a more high-level approach. It is sometimes called as “goal-directed motion”. Given the positions of end-effectors only, the inverse kinematics solves the position and orientation of all the joints in the hierarchy. Mathematically, it is expressed as

$$\Theta = f^{-1}(x) \tag{2.2}$$

That is, given x, derive Θ.

Inverse kinematics was mostly used in the robotics. The studies in this area are then adapted to the computer animation. Contrary to forward kinematics, inverse kinematics provides direct control over the movement of the end-effector. On the other hand the inverse kinematic problems are difficult to solve where, in forward kinematics, the solution is found easily by multiplying local transformation matrices of joints in a hierarchical manner. The inverse kinematics problems are non-linear and for a given position x there may be more than one solution for Θ.

Mainly, there are two approaches to solve inverse kinematics problem: *Numerical and analytical methods.*

2.2.2.1 Numerical Methods

The most common solution method for the non-linear problem stated in Equation 2.2 is based on the linearization of the problem by means of its current configuration [49]. When we linearize the problem the joint velocities and the end-effector velocity will be related by:

$$\dot{x} = J(\Theta)\dot{\Theta} \tag{2.3}$$

As it is denoted in the Equation 2.3, the relation is expressed by the *Jacobian* matrix:

$$J = \frac{\delta f}{\delta \Theta} \tag{2.4}$$

This matrix relates the changes in the joint variables (δf) with the changes in the position of the end-effector ($\delta \Theta$) in an $m \times n$ manner, where m is the joint variables count and n is the dimensions of the end-effector vector.

When we invert the Equation 2.3 we reach the formula:

$$\dot{\Theta} = J^{-1}(\Theta)\dot{x} \tag{2.5}$$

So it is clear that given the inverse of Jacobian, computing the changes in the joint variables due to the change in the end-effector position is trivial. We can develop an *iterative algorithm* for the solution of this inverse kinematic problem. Each iteration computes the $\dot{x}$ value by using actual and goal position vectors of end-effector. The iteration continues till the goal position of the end-effector is reached. However, in order to compute the joint velocities, ($\dot{\Theta}$) we must find the $J(\Theta)$ value for each iteration.

At each iteration, we are trying to determine the end-effector frame movements with respect to joint variable changes. The frame movements are denoted by the columns of the Jacobian matrix J, and for a given joint variable vector (Θ), determined by the position (P(Θ)) and orientation (O(Θ)). So, the Jacobian column entry for the ith joint is:

$$J_i = \begin{bmatrix} \delta P_x/\delta\Theta_i \\ \delta P_y/\delta\Theta_i \\ \delta P_z/\delta\Theta_i \\ \delta Q_x/\delta\Theta_i \\ \delta Q_y/\delta\Theta_i \\ \delta Q_z/\delta\Theta_i \end{bmatrix} \tag{2.6}$$

These entries can be calculated as follows: Every joint i in the system translates along or rotates above a local axis u_i. If we denote the transformation matrix between local frames and world frames as M_i, the normalized transformation of the local joint axis will be:

$$axis_i = u_i M_i \tag{2.7}$$

By using Equation 2.7, we can calculate the Jacobian entry either for a translating joint by:

$$J_i = \begin{bmatrix} [axis_i]^T \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{2.8}$$

or for a rotating entry by:

$$J_i = \begin{bmatrix} [(p - j_i) \times axis_i]^T \\ (axis_i)^T \end{bmatrix} \tag{2.9}$$

At that point, we want to state that linearization solution makes an assumption that the Jacobian matrix is invertible (both square and non-singular), while this is not the case in general. In case of redundancy and singularities of the manipulator, the problem is more difficult to solve and new approaches are needed.

2.2.2.2 Analytical Methods

In contrast with the numerical methods, analytical methods find solutions in most cases. We can classify the analytical methods into two groups; closed-form or algebraic elimination based methods [15]. Closed-form method specifies the joint variables by a set of closed-form equations and generally applies to six degree of freedom systems with special kinematic structure. On the other hand, in algebraic elimination based method, the joint variables are denoted by a system of multivariable polynomial equations. Generally, the degree of these polynomials are greater than four. That is why, algebraic elimination methods still require numerical solutions. In general, analytical methods are more likely than the numerical ones because analytical methods find all solutions and are faster and more reliable.

2.2.3 Discussion

The main advantages of kinematics are as follows: Firstly the motion quality is based on the model and the animator's capability. The second advantage is the low cost of the computations. On the other hand in both kinematic methods, the animator still spends lots of time in order to produce movement. In other words, the methods can not produce movement in a dynamic manner by means of the physical laws as in the real world. Moreover, the interpolation process of the algorithms leads to loss of realism in the animation.

When we reviewed the literature we saw that Chadwick et al. had used inverse kinematics in creating keyframes [14]. Welman investigates the inverse kinematics in detail and describes the constrained inverse kinematic figure manipulation techniques [42]. Badler et al. also proposed an inverse kinematic algorithm in order to constraint the positions of the body parts during animation [2]. In addition, Girard and Maciejewski [18] and Sims and Zeltzer [35] generated leg motion by means of inverse kinematics. Their systems are composed of two stages: In the first stage, foot trajectories are specified, and in the second one, the inverse kinematic algorithm computes the leg joint angles during movement of the feet.

2.3 Dynamics

Physical laws heavily affect the realism of a walking motion. In this sense, dynamics approaches may be used for animating walking models. But these approaches require more physical constraints such as center of mass, total mass and inertia. Fundamental principles of dynamics are originated from Newton's laws and can be stated by following:

$$f = m \times \ddot{X} \tag{2.10}$$

where f represents the force applied to an object, m is its mass and $\ddot{X}$ denotes the second derivative of the position vector X with respect to time. The dynamics methods can be classified in two main parts: the *forward dynamics* and the *inverse dynamics*.

2.3.1 Forward Dynamics

Basically, forward dynamics considers applying forces on the objects. These forces can be applied automatically or by the animator. The motion of the object is then computed by solving the equations of the motion for the object as a result of these forces. Wilhelm gives a brief summary of rigid body animation by means of forward dynamics methods [45]. Although the method works well with a rigid body, the simulation of articulated figures by forward dynamics is more complicated. Because, the equations of motion for articulated bodies must also handle the interaction between the body parts. This extension in the equation makes the control hardly difficult. Nevertheless, more than fifteen years ago, Virya system tried to simulate an articulated figure by forward dynamics methods [43]. This attempt was followed by many others [1, 46].

The main drawback of the forward dynamic simulation is that, not having an accurate control mechanism makes the method useful for the tasks in which initial values are known.

2.3.2 Inverse Dynamics

In the contrary, inverse dynamics is a goal oriented method in which forces needed for a motion are computed automatically. Although the inverse dynamics applications are rarely used in computer animation, Barzel and Barr [7] were the first users of the method. They generated a model composed of objets which are geometrically related. This relations are presented by constraints that are used to denote forces on a object. These forces animate the figure directed to a goal in which all the constraints are satisfied. The Manikin system proposed by Forsey and Wilhelm [17] also animated articulated model by means of inverse dynamics. The system computes the needed forces when a new goal position for the figure is specified. An other approach was introduced by Isaac and Cohen [24] which was called as Dynamo system and based on keyframed kinematics and inverse dynamics. This method is an example of combination of dynamic simulation and kinematic control. Ko also developed a real-time algorithm for animating human locomotion using inverse dynamics, balance and comfort control [26].

All the studies stated above describes the motion of a figure by considering geometric constraints. On the other hand, researchers developed some inverse dynamics solutions based on non-geometric constraints. Brotman and Netravali [9], Girard [19] and Lee et al. [29] are some examples of these researchers.

2.3.3 Discussion

The composition of the anatomical knowledge with the inverse dynamics approach generates more realistic motion. This composite system can also handle the interaction of the model with the environment. That is why, this method is useful for virtual reality applications. However, dynamic techniques are computationally costly than the kinematic techniques and hardly used in interactive animation tools.

Using purely a direct dynamics system or an inverse dynamics system has problems. To have the desired motion and use high level control, hybrid solutions should be applied. The need for the combination of forward and inverse dynamics is discussed in [30].

2.4 Motion Capture

Since dynamics simulation could not solve all animation problems, new approaches were introduced. One of these methods animates virtual models by using human motion data generated by motion capture techniques. It is mainly used in the film and computer games industries.

Parallel to the technological developments, the movement of an real actor can be captured by using magnetic or optical technologies. The 3D positions and orientations of the points located on the human body are stored, and this data is then used in animation to map into a model. Realistic motion generation in a very short time and with high details is the main advantage of that method. Moreover, with additional computations, the 3D motion data is adapted to new morphology. *Motion blending* and *motion warping* are the two techniques to obtain different kind of motions.

Motion blending needs different characteristic motions. It just interpolates between the parameters of motions. It has the advantage of low computation cost. Motion warping techniques take the motion trajectories and change the motion by modifying these trajectories. But the method suffers from the same problem of kinematic or procedural animation techniques. Since these modifications can not handle dynamics effects, it is impossible to ensure that resulting motions are realistic.

In their studies, Bruderlin and Williams [12] worked on signal processing techniques in order to alter existing motions. Unuma et al. [40] generated human figure animations by using Fourier expansions on the available motions.

2.4.1 Discussion

In contrast with the procedural and kinematic techniques, motion modification techniques provide the usage of real-life motion data for animating the figures. This results with the advantage of obtaining natural and realistic looking motion in an enhanced production speed. On the other hand, this method is not an convenient method when we want to modify the motion captured data. The realism can be lost in large changes of captured data.

2.5 Motion Control

The parameters of objects should be determined at each frame when a character is animated by using kinematic methods. However, determining the parameters explicitly at each frame, even for a simple motion, is not trivial. The solution for this problem is to specify a series of keyframe poses at different frames. Following this approach, an animator only needs to specify the parameters at the keyframes. Parameter values for the intermediate frames, called in-betweens, between two keyframes are obtained by interpolating the joint parameters between those keyframes. Then, successively displaying each intermediate pose gives the entire animation of the figure [31].

Another problem arises when searching a suitable interpolation method. Linear interpolation is the simplest method to generate intermediate poses, but it gives unsatisfactory motion. Due to the discontinues first derivatives in the interpolated joint angles, the method generates a robotic motion. Therefore, obtaining more continuous velocity and acceleration requires the usage of higher order interpolation methods like piecewise splines. Keyframe interpolation is explained in [20, 22, 34, 38].

2.5.1 Interpolation Control

Intermediate values produced by interpolation, generally does not satisfy the animator. Therefore, the interpolation process should be kept under control [28]. For just a single DOF, the intermediate values constitute a trajectory curve which passes through the keyframes values. Interpolating spline along with the keyframed values at both end determines the shape of the trajectory. An interactive tool that shows the shape of a trajectory and enables an animator to change the shape, can be useful. After a trajectory is defined, traversing it at a varying rate can improve the quality of the movement. Some parameterized interpolation methods controlling the shape of a trajectory and the rate at which the trajectory is traversed have been suggested.

An interpolation technique which relies on a generalized form of piecewise cubic Hermite splines was described by Kochanek and Bartels [27]. At the keyframes, the magnitude and direction of tangent vectors (tangent to the trajectory) are controlled by adjusting *continuity*, *tension* and *bias*. Changing the direction of the tangent vectors, locally, controls the shape of the curve when it passes through a keyframe. On the other hand, the rate of change of the interpolated value around the keyframe is controlled by changing the magnitude of the tangent vector. Some animation effects such as action follow through and exaggeration [28] can be obtained by setting the parameters. This method does not have the ability to adjust the speed along the trajectory without changing the trajectory itself because three parameters used in the spline formulation influence the shape of the curve.

Steketee and Badler [37] offered a double interpolant method in which timing control is separated from the trajectory itself. Similar to the previous method, a trajectory is a piecewise cubic spline that passes through the keyframed values. In addition, the trajectory curve is sampled with a second spline curve. By this way, the parametric speed at which the trajectory curve is traversed is controlled. Unfortunately, there is no one-to-one relation between actual speed in the geometric sense and parametric speed. Therefore, desired velocity characteristic is obtained via a trial-and-error process.

A way to obtain more intuitive control over the speed is to reparameterize the trajectory curve by arc length. This approach provides a direct relation between parametric speed and geometric speed. An animator can be provided an intuitive mechanism to vary speed along the trajectory by allowing him to sketch a curve that represents distance over time [6].

In the traditional animation, key animation frames are drawn by experienced animators and intermediate frames are completed by less experienced animators. In this manner, keyframe based approach and traditional animation are analogous. The problem with the keyframe based animation is that it is not good at skeleton animation. The number of DOF is one of the main problems. When the number of DOF is high, an animator has to specify too many parameters for even a single key pose. It is inevitable that controlling the motion by changing lots of trajectory curves is a very hard process. The intervention of the animator should be at low levels, may be some control at joints.

Another problem arises due to the hierarchical structure of the skeleton. Since the positions of all other objects depend on the position of the root joint, the animator hardly determines the positional constraints in keyframe pose creation. The problem can be solved by specifying a new root joint and reorganizing the hierarchy but it is rarely useful. Interpolation process also suffers from the hierarchical structure of the skeleton. You can not calculate the the correct foot positions at the intermediate frames by only interpolating joint rotations.

Chapter 3

ARTICULATED FIGURE MODELING

Although modeling the basic structure of the articulated figure is the trivial part of human modeling, challenges can arise when there is no standard for this. H-Anim 1.1 Specification is mainly used as a standard for human body modeling [36]. This standard defines the geometry and the hierarchical structure of the human body.

A simple XML data format to represent the human skeleton is defined by conforming the hierarchy of joints and segments of human body and their naming conventions used in the H-Anim 1.1 Specification. XML provided us an excellent method for describing and defining the skeleton data due to its structured and self-descriptive format.

3.1 XML Based Model

To make an introduction to the XML data format that we adopted for articulated figure modeling, a portion of the XML data for the human figure used is given in

Figure 3.1. The complete human figure in XML format is given in Appendix A.2. The Document Type Definition (DTD) of the human body representation that is used in XML format that defines humanoid is presented in Appendix A.1.

```xml
<Joint name="HumanoidRoot" center="0.1296 0.0000 -3.8563">
   <Joint name="sacroiliac" center="0.0075 0.0000 -4.2920">
       <Joint name="l_hip" center="-0.0005 -0.4446 -4.2920"
       limitx="-1.00 2.00" limity="-1.40 2.90" limitz="-1.40 1.30">
           <Joint name="l_knee" center="0.1441 -0.4446 -2.2778"
           limity="-3.00 0.00">
               <Joint name="l_ankle" center="-0.3444 -0.4446
               -0.3070">
                   <Joint name="l_midtarsal" center="0.1722 -0.4446
                   -0.0005" />
               </Joint>
           </Joint>
       </Joint>
       <Joint name="r_hip" center="0.0136 0.4446 -4.2920"
       limitx="-1.00 2.00" limity="-1.40 2.90" limitz="-1.40 1.30">
           <Joint name="r_knee" center="0.1488 0.4446 -2.2993"
           limity="-3.00 0.00">
               <Joint name="r_ankle" center="-0.3585 0.4446
               -0.3332">
                   <Joint name="r_midtarsal" center="0.1722 0.4446
                   0.0000" />
               </Joint>
           </Joint>
       </Joint>
   </Joint>
```

Figure 3.1: A portion of humanoid data in XML format.

The nodes in H-Anim 1.1 Specification (Humanoid, Joint and Segment) are used as elements in XML to construct a hierarchy that corresponds to the skeleton. In this format, the following attributes are used for joint nodes. `center` attribute is used for positioning the associated element. `name` attribute specifies the name of associated element. `limitx`, `limity`, and `limitz` attributes are used for setting the upper and lower limits for the joint angles, respectively.

Although the data format stated above can be used for representing the full skeleton specified in the H-Anim standard, we do not need completely define all the joints in our application. The complete hierarchy is too complex for most of the applications. For example, in real-time applications such as games, there is no need to use the full set of joints. A simplified hierarchy will be more suitable for most of the games. Fortunately, in H-Anim 1.1 Specification document, four "Levels of Articulation" that contain the subsets of the joints are suggested. The body dimensions and level of articulations are suggested for information only and are not specified by the H-Anim standard. Behind the simplicity goal, one other reason for suggesting level of articulations is the compatibility. Conforming to a level of articulation, the animators could share their animations and humanoids to the same (or higher) level of articulation. After dissecting the level of articulation, a more simplified version of "Level of Articulation Two" seems appropriate for our work. Because, "Level of Articulation One" represents a typical low-end real-time 3D hierarchy and it does not contain information about the spine. Besides, the shoulder complex is not much detailed. On the other side, "Level of Articulation Two" represents much information that is needed about spine, skull and hands. "Level of Articulation Three" represents the full H-Anim hierarchy.

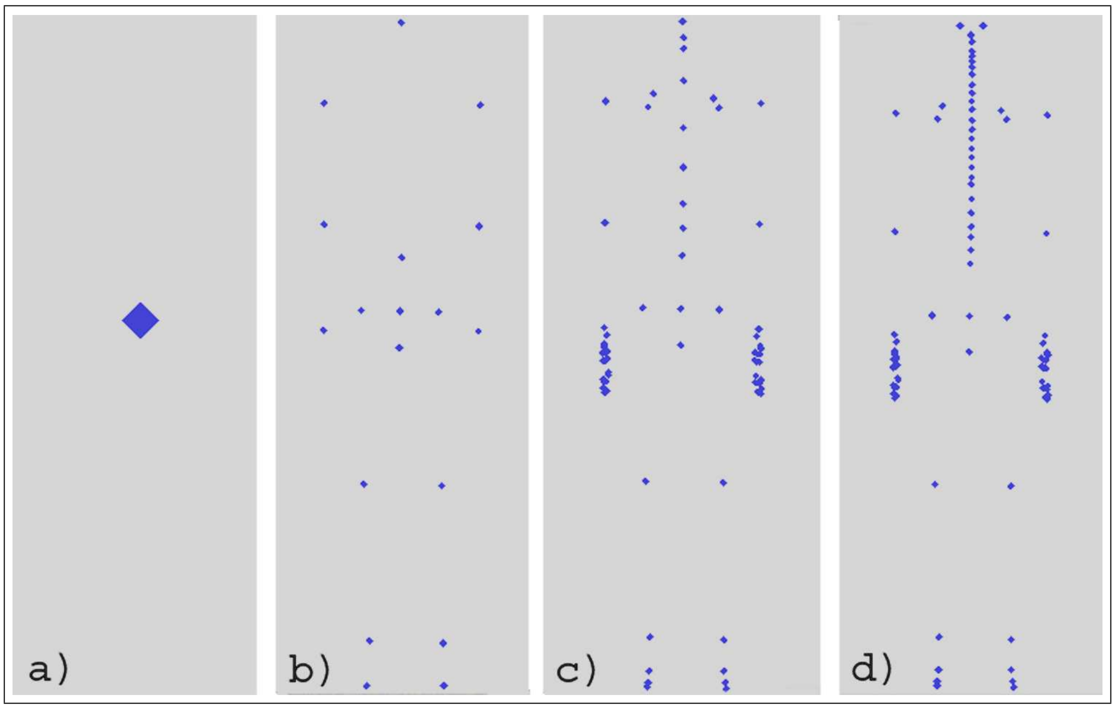


Figure 3.2: Level of articulations: a) level of zero, b) level of one, c) level of two, and d) level of three.

A front and left view of the skeleton corresponding to the XML based model in Appendix A.2 is represented in Figure 3.3.

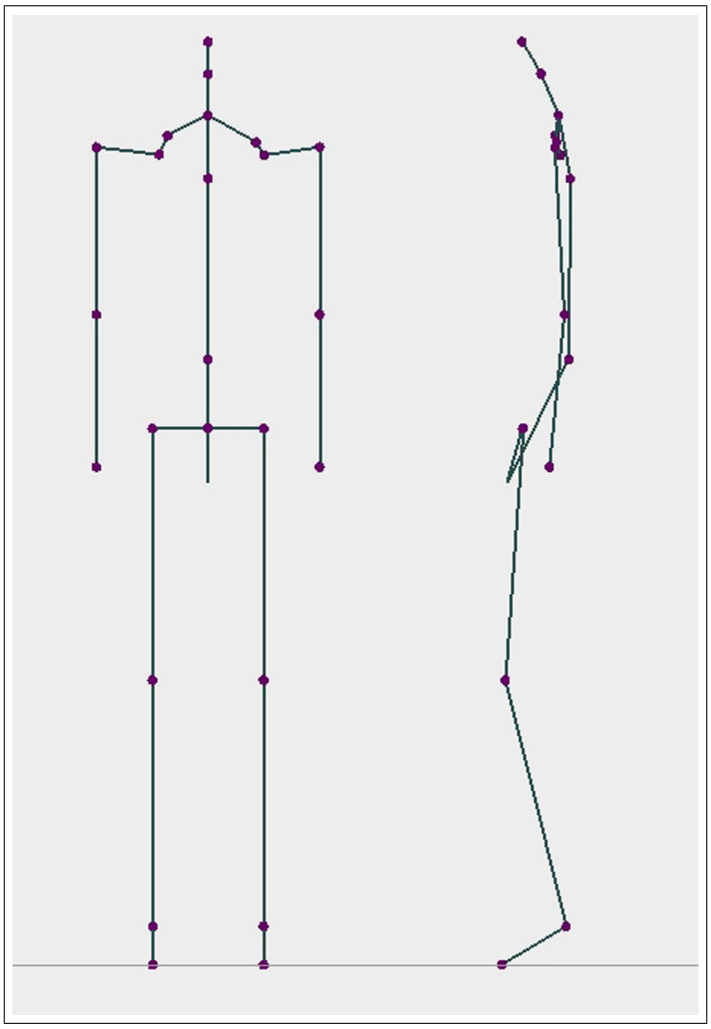


Figure 3.3: Left and top view of the skeleton.

Moreover, a framework is implemented to parse the skeleton data and construct an abstract skeleton data type. C++ is used for the implementation of the system. All the classes are grouped in a package, named `Hbody`. The `Hbody` package contains the following classes: `Humanoid, Joint, Segment, Site, and Node.`

The `Hbody` package supports the creation and manipulation of the body structure defined by a file in XML format that conforms to the DTD given in Appendix A.1. A simple XML parser, TinyXml [39], is used to parse the XML data.

The UML class diagram is shown in Figure 3.4 to graphically illustrate the classes hierarchy for the system implementation.

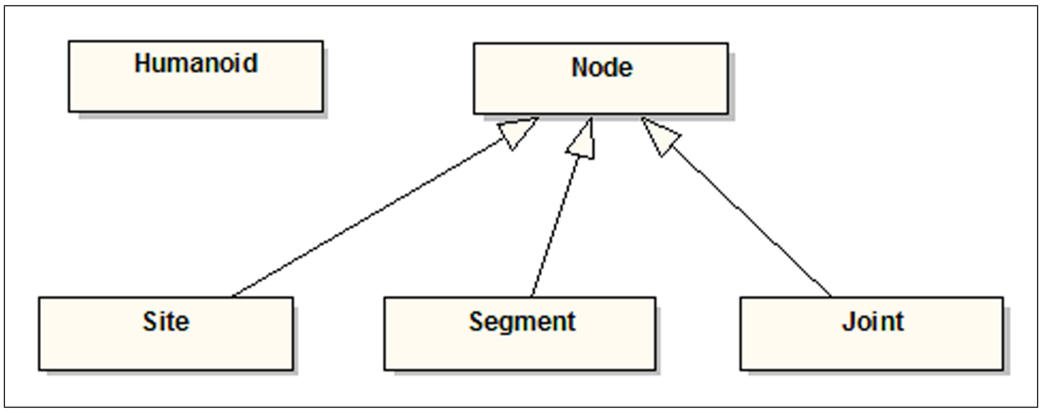


Figure 3.4: UML class diagram of the `Hbody` package.

`Humanoid` class is used to define the abstract data type humanoid. It stores information (such as author, copyright, gender of humanoid, etc) about humanoid. It can act as a group of hierarchical nodes. It also stores references to all `Joints`, `Segments`, and `Site` nodes in a vector structure for quick access to nodes. Briefly, `Humanoid` class serves as a wrapper for the humanoid.

`Node` class is the base class for the classes `Joint, Segment` and `Site`. This class stores a list of child nodes which is needed to define the hierarchy. `Joint` and `Segment` classes are used to define the joints and segments in human body structure. `Site` class is used as an end-effector for inverse kinematics. `Joint, Segment` and `Site` classes inherit the members and functionality of base class `Node`. So, all these classes can take part in the hierarchical structure constructed by using `Node` objects.

This package can be used to represent various articulated structures, like humans, animals and robots, since it is designed and implemented in a generic way.

Chapter 4

MOTION CONTROL

The control of human motion has always been a challenging problem in computer animation. Numerous studies in fields such as biomechanics, robotics, animation, ergonomics, and psychology are integrated to have realistic human motion control techniques. The motion control can be classified in two categories according to the level of abstraction that specifies the motion; *low-level* and *high-level* systems. A *low-level system* needs to specify the motion parameters (such as position, angles, forces, and torques) manually. In a *high-level animation system*, motion is specified by abstract terms such as “walk”, “run”, “grab that object”, “walk happily”, etc. At higher levels, the low level motion planning and control tasks are done by the machine. The animator just changes some parameters to obtain different kind of solutions. This study especially focuses on the low-level control of motion using kinematic methods. *Spline-driven animation techniques* are used to specify the characteristics of the motion. In addition, a high-level walking animation mechanism that make use of these low-level techniques are described.

4.1 Low-Level Control of Motion

In the study, spline-driven animation method is used as a low-level control mechanism. In this technique, motion characteristics of an object are specified by using splines. The trajectories of limbs (paths of pelvis, ankles in a human walking animation) in a human motion are controlled by splines. Besides, using a conventional keyframing technique the joint angles over time are determined by splines. Since splines are smooth curves, they can be used in interpolation of smooth motions in space. Moving an object along a smooth path is supplied with smooth spline curves.

There are several different kinds of splines that are used for different kind of purposes in graphics applications. *Cubic splines* are one of them that have been extensively used. Since they require less calculations and memory and allow local control over the shape of the curve, cubic splines are the mostly preferred ones. We can use these splines not only in setting up paths for object motions but also in designing object shapes. One other advantage is that, compared with the lower-order polynomials it is more flexible for modeling arbitrary curve shapes [23].

For a set of control points, cubic splines are generated by a piecewise polynomial curve that passes through every control points. We can denote the curve with:

$$p_k = (x_k, y_k, z_k), \quad k = 0, 1, 2, ..., n \tag{4.1}$$

The cubic spline generated from these control points is presented in Figure 4.1. The parametric cubic polynomial that is to be fitted between each pair of control points is represented by followings:

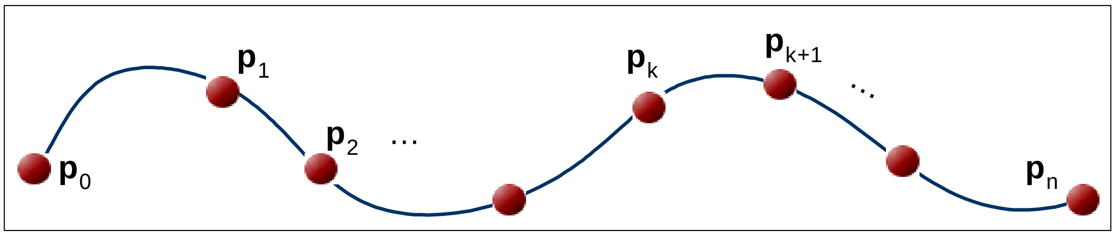


Figure 4.1: A piecewise continuous cubic-spline interpolation of $n+1$ control points.

$$\begin{bmatrix} x_u \\ y_u \\ z_u \end{bmatrix} = \begin{bmatrix} a_x u^3 + b_x u^2 + c_x u + d_x \\ a_y u^3 + b_y u^2 + c_y u + d_y \\ a_z u^3 + b_z u^2 + c_z u + d_y \end{bmatrix}, \quad (0 \leq u \leq 1) \tag{4.2}$$

One class of cubic splines, natural cubic splines, is one of the first spline curves to be developed for needs of computer animation. This curve is a mathematical representation of the original drafting spline. It has C^2 continuity because, the formulation of these splines requires two adjacent curve section to have the same first and second parametric derivatives. Beyond the advantage of being a mathematical model for drafting spline, natural cubic splines have a big drawback that they do not allow local control. That means changing the position of any control point results with a alteration in the entire curve.

Hermite spline is another class of cubic splines that is represented by an interpolating cubic polynomial with a specified tangent at each control point [5]. Contrary with the natural cubic splines, Hermite splines provide local control because each curve section is only related with its endpoints. A sample Hermite curve section is illustrated in Figure 4.2.

Although Hermite polynomials can be useful for some digitizing applications, for most computer graphic applications, it is preferable to generate spline curves without requiring input values for curve slopes or other geometric constraints. Detailed information about Hermite splines can be found in [23].

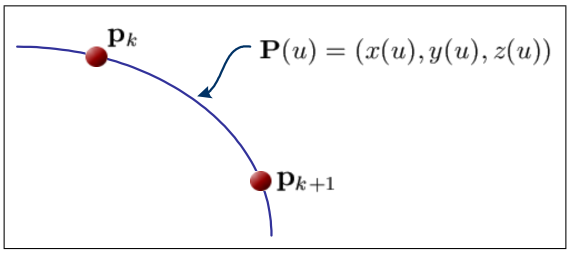


Figure 4.2: Parametric point function $P(u)$ for a Hermite-spline section.

Like Hermite splines, Cardinal splines interpolates piecewise cubics with specified endpoint tangents at the boundary of each curve section with an exception that Cardinal splines does not require the values for the endpoint tangents. Instead, the value of the slope of a control point is calculated from the coordinates of the two adjacent points.

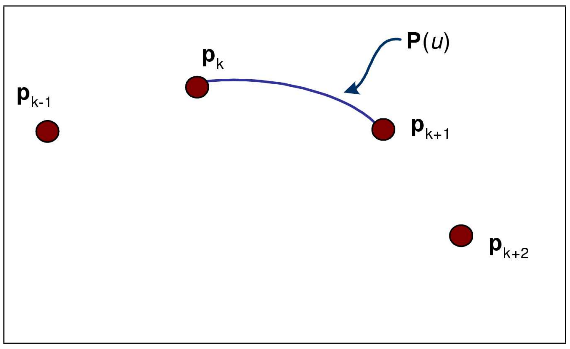


Figure 4.3: Parametric point function $P(u)$ for a Cardinal-spline section.

A Cardinal spline section is specified with four consecutive control points. The middle two points are the endpoints and the other two are used to calculate the slope of the endpoints. As it is seen in the Figure 4.3, if we present the parametric cubic point function for the curve section between control points P_k and P_{k+1} with $P(u)$ then, the boundary conditions for the Cardinal spline section is formulated by the following equations:

$$\begin{aligned}
P(0) &= p_k, \\
P(1) &= p_{k+1}, \\
P'(0) &= \frac{1}{2}(1-t)(p_{k+1}-p_{k-1}), \\
P'(1) &= \frac{1}{2}(1-t)(p_{k+2}-p_k),
\end{aligned} \tag{4.3}$$

where parameter t, tension parameter, controls how loosely or tightly the Cardinal spline fits the control points. When t=0, this class of curves are named as Catmull-Rom splines, or Overhauser splines [13].

We can generate the boundary conditions formulation as:

$$P_u = \begin{bmatrix} u^3 & u^2 & u & 1 \end{bmatrix} \cdot M_C \cdot \begin{bmatrix} p_{k-1} \\ p_k \\ p_{k+1} \\ p_{k+2} \end{bmatrix}, \tag{4.4}$$

where the Cardinal matrix is:

$$M_C = \begin{bmatrix} -s & 2-s & s-2 & s \\ 2s & s-3 & 3-2s & -s \\ -s & 0 & s & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}, \quad s = \frac{(1-t)}{2}, \tag{4.5}$$

where t is the tension parameter.

One other cubic spline class is the Kochanek-Bartels splines, which is an extension of the Cardinal splines. Kochanek-Bartels splines include two additional parameters in order to have the flexibility in adjusting the shape of the curve sections. Kochanek-Bartel splines are especially designed for modeling the animation paths.

In our system we used Cardinal splines, which are very powerful and have controllable input control points fitting mechanism with a tension parameter. The UML class diagram of the implemented curve classes is shown in Figure 4.4 that graphically illustrates the classes.

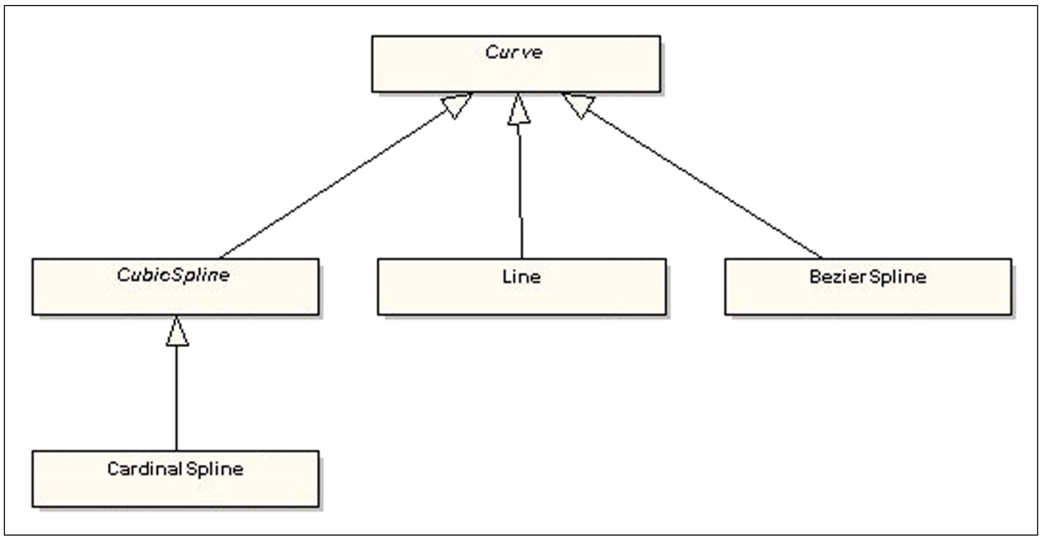


Figure 4.4: UML class diagram of the `Curve` package.

The paths for pelvis, ankle and wrist motions are specified using Cardinal spline curves. These are considered as position curves. Besides, a velocity curve is specified independently for each object. Thus, just affecting the velocity curve, characteristics of the motion can be changed. Steketee and Badler were the first to recognizing this powerful method [37]. They called this velocity curve as "kinetic spline". The method is called "double interpolant" method. Kinetic spline may also be interpreted as a distance curve. Given a distance curve or velocity curve, velocity curve or distance curve can be easily calculated.

Our application makes use of the "double interpolant" by enabling the user to specify a position spline and a kinetic spline. The kinetic spline, Velocity curve, V(t), is commonly used as the motion curve. However, V(t) can be integrated to determine distance curve, S(t). These curves are represented in two-dimensional space for easy manipulation. Position curve is a three-dimensional curve in space, through which the object moves. Control of motion involves editing the position and kinetic splines. In our application velocity curves, and distance curves are straight lines and Cardinal splines, respectively. `Line`, which graphically depicts a straight line, and `CardinalSpline` classes in Figure 4.4 are used to represent the curves.

Furthermore, a problem arises while moving an object along a given position spline because of the parametric nature of cubic splines. Suppose we had a velocity curve and a position curve to control the motion. We can find the distance travelled at a given time by having the integral of the velocity curve with respect to time. Now we must find a point along the position spline, where the computed distance is mapped.

If we formulate the problem; we have a path specified by a spline $Q(u)$, $(0 \leq u \leq 1)$ and we are looking for a set of points along the spline such that, the distance travelled along the curve between consecutive frames is constant. Basically, these points can be computed by evaluating $Q(u)$ at equal values of u. But this requires the parameter u to be proportional to the arclength, the distance travelled along the curve. Unfortunately, this is not the case in general. In the special cases where the parameter is proportional to arclength, the spline is said to be parameterized by arclength. Figure 4.5 illustrates a spline with 10 points of equal intervals of u and 10 points located at equal intervals of arclength. As it is seen from the figure, without the arclength parameter an object can hardly move with a uniform speed along a spline. This arclength problem can be solved by using the arclength parameterization of spline curve [21, 41].

Cardinal spline curves provide the required functionality for motion control. They can be constructed with a few set of control points and can be manipulated easily. Having these advantages, a motion control system is implemented in which the animator constructs the position and kinetic splines for the joints ankle, wrist and pelvis. Figures 4.8 and 4.9 illustrate the distance and velocity

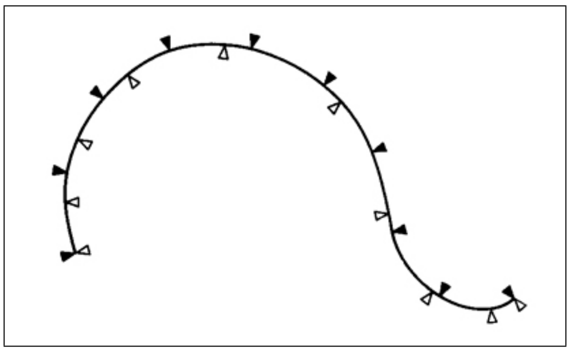


Figure 4.5: Intervals of equal parametric length (outlined arrowheads) do not correspond to equal intervals of arclength (black arrowheads) (reprinted from [41]).

curves that utilizes the `CardinalSpline` and `Line` classes. In Figures 6.2 and 6.3, the position curve that utilizes the `CardinalSpline` class is shown. The animator interactively shapes the curves, and view the resulting animation in real time. Double interpolant method enables the animator to change characteristics of the motion independently. This can be done by editing different curves that correspond to the position in 3D space, distance, and velocity curves independent from each other. However, the result of change in kinetic spline curve should be controlled in the position curve in order to have the desired motion.

After constructing the position curves for end effectors like wrist and ankles, goal-directed motion control technique is used to determine the joint angles of shoulder, hip, elbow and knee over time. Using a inverse kinematics method to determine the position and orientation of upper joints along the hierarchy really simplifies the control of motion. The animator only moves the end-effector and the orientations of other links in the hierarchy are computed by inverse kinematics.

In addition, our system enables the user to define the joint angles which are not computed by the inverse kinematics program. Using a conventional keyframing technique, the joint angles over time can be specified by the user. Cardinal splines are used to have a smooth interpolation of joint angles.

In this fashion, the system provides a low-level animation system to the user in which one can obtain any kind of motion by specifying a set of spline curves for position, distance and joint angles over time. Besides, our application enable the user to save and load, and animate the defined motions. The user interface of the application is described in Appendix C.

Furthermore, using these low-level techniques, a high-level motion mechanism for walking is provided which is explained in the following section.

4.2 Human Walking Behaviour

Most of work in motion control has aimed to provide high level controls to produce complex motions like walking. Kinematics and dynamic approaches for human locomation are described by many researchers [4, 8, 10, 11, 19, 25, 44, 48]. Many approaches are introduced for the animation of human walking. A survey of human walking is given in [32].

In our system walking motion can be controlled using kinematic approaches in high level by allowing the user to specify a few number of *locomotion parameters*. Specifying the straight travelling path on flat ground without obstacles and the speed of locomotion, our system generates the walking automatically, by computing the 3D path information and the low-level kinematics parameters of body elements. Furthermore, some extra parameters such as the size of walking step, the time elapsed during double-support, rotation, tilt, and lateral displacement of pelvis can be adjusted by the user to have a different walking motion.

Walking is a smooth, symmetric motion in which the body, feet, and hands move rhythmically in the required direction with a speed. Basically, it can be characterized as the succession of phases separated by the state of foots because, the feet drive the main part of the animation. During walking, foot has contact with the ground (*footstrikes*) and leaves the ground (*takeoffs*) successively. The *stride* is defined as the walking cycle in which four footsrikes and takeoff events occur. The part of this cycle, which is between the takeoffs of the two feet, is called a *step*. In this concept, the phases for each leg can be classified into two phases: The *stance* and the *swing phases*. The stance phase is the period of support. The swing phase is the non-support phase. In the locomotion cycle, each leg pass through both the stance and swing phases. In the cycle, there is also a period of time where both of the legs are in contact with the ground. The phase is called as *double-support*. The phases of walking cycle can be seen in Figure 4.6

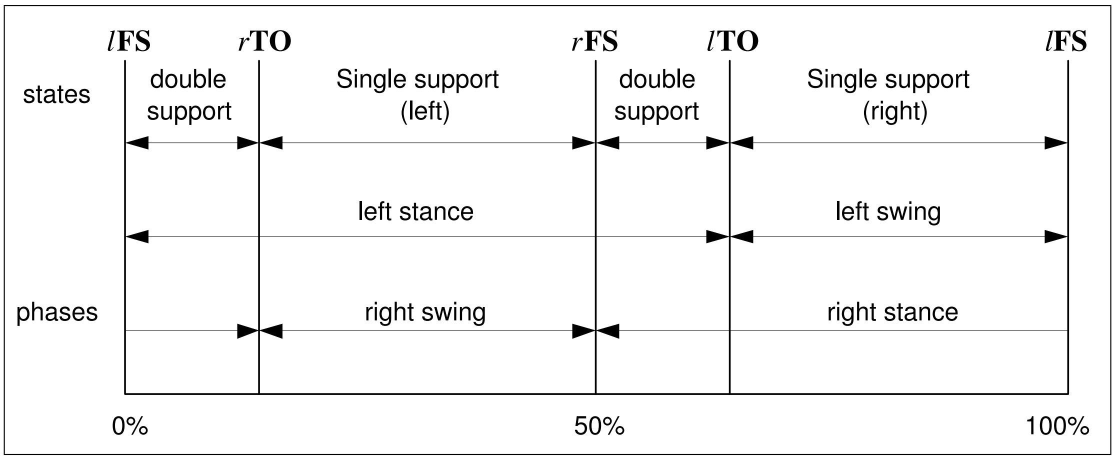


Figure 4.6: Locomotion cycle for bipedal walking (adopted from [32]).

Furthermore, walking has some special characteristics. One foot is in contact with the ground at all times and for a period both of the feet are in contact with the ground. In addition the motion is cyclic. These characteristics of walking really simplify the control mechanism. However, natural human walking animation is a challenging problem. The kinematics nature of walking should be more dissected for a realistic walking motion. For this purpose, Saunders et al. defined a set of *gait determinants*, which mainly describe the movement of pelvis motion [33]. These determinants are *compass gait, pelvic rotation,* *pelvic tilt, stance leg flexion, planar flexion of the stance angle*, and *lateral pelvic displacement.*

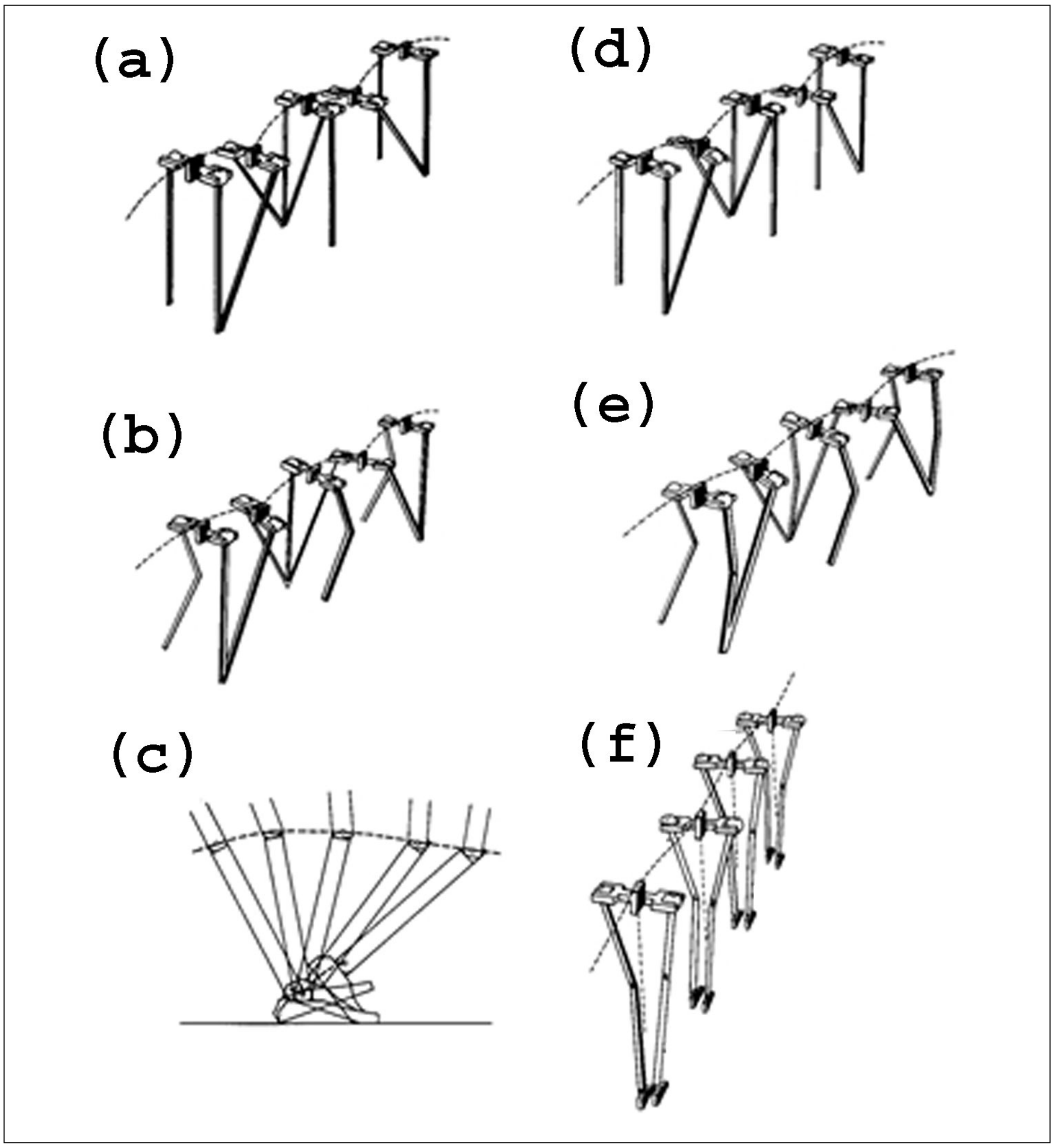


Figure 4.7: Walking gaits: (a) compass gait, (b) pelvic tilt, (c) plantar flexion, (d) pelvic rotation, (e) stance leg inflexion, and (f) lateral pelvic displacement (reprinted from [41]).

1. *Compass gait* (Figure 4.7(a)) The legs remain straight, moving in parallel planes. The pelvis moves in a series of arcs whose radius is determined by the leg length.

2. *Pelvic tilt* (Figure 4.7(b)) If the pelvis is allowed to tilt as well as rotate the arc of its trajectory can be further flattened. In practice the hip on the 'swing' side of the walk falls below the hip on the 'stance' side. This lowering occurs immediately after the end of the double support phase and the 'toe-off' of the swing leg. Introducing a pelvic tilt necessarily involves a knee flexion of the swing leg.

3. *Plantar flexion of the stance angle* (Figure 4.7(c)) The transition between the double support phase and the swing phase is made smoother if the angle of the stance leg moves down just prior to toe-off. This means that the foot must flex with respect to the shin.

4. *Pelvic rotation* (Figure 4.7(d)) Allowing the pelvis to rotate about a vertical axis through its center enables the length of the step to be increased and the arc to be flattened. Saunders et al. quote ± 3 degrees for the amplitude of this motion.

5. *Stance leg flexion* (Figure 4.7(e)) The next elaboration is stance leg flexion where the pelvic trajectory arc is further flattened.

6. *Lateral pelvic displacement* (Figure 4.7(f)) Normal walking involves displacement of the pelvis from side to side, as the weight is transferred from one limb to another [41].

In our system, compass gait, pelvic rotation, pelvic tilt, and lateral pelvic displacement is considered. In pelvic rotation, pelvis rotates about the body to the left and the right, relative to the walking direction. Saunders et al. quote 3 degrees for the amplitude in a normal walking gait. In normal walking, the hip of the swing leg falls slightly below the hip of the stance leg. This event occurs for the side of swing leg, after the end of the double support phase. 5 degrees is considered for the amplitude of pelvis tilt. In lateral pelvic displacement, the pelvis moves from side to side. Immediately after the double support, the weight is transferred from center to the stance leg. So, a pelvis moves alternately during a normal walking. Moreover, individual gait variations can be obtained by determining the parameters of these pelvis activities. Our system enables the user to specify these parameters and observe the walking animation carefully.

The main parameters of walking behavior are the velocity and step length. Walking can have different variations by changing these parameters. However, experimental results show that these parameters are somehow related. Inman et al. [33] related the walking speed to walking cycle time and Bruderlin and Calvert [10] stated the correct time durations for a locomotion cycle. Based on the experimental works on walking, the followings can be stated:

$$velocity = stepLength \times stepFrequency \tag{4.6}$$

$$stepLength = 0.004 \times stepFrequency \times bodyHeight \tag{4.7}$$

Experimental data shows that maximum value of *stepFrequency* is 182 steps per minute. Time for a cycle can be calculated from the step frequency:

$$tcycle = 2 \times tstep = \frac{2}{stepFrequency} \tag{4.8}$$

Using the Figure 4.6, time for double support (*tds*) and and the single support phases can be calculated using the formula :

$$tstep = tstance - tds \tag{4.9}$$

$$tstep = tswing + tds \tag{4.10}$$

Based on the experimental results *tds* is calculated as [33]:

$$tds = (-0.0016 \times stepFrequency + 0.2908) \times tcycle \tag{4.11}$$

Although *tds* could be calculated automatically if the *stepFrequency* is given, it is sometimes convenient to redefine *tds* to have walking animations with various characteristics.

By utilizing the groups of formula, which define the kinematics of walking, a velocity curve (time vs. velocity) is constructed for the left and right ankles. Figure 4.8 is shown to graphically illustrate the velocity of left and right ankles versus time. The distance curves shown in Figure 4.9 are automatically generated using the velocity curves. Ease-in, ease-out effect which is generated by speed up and slow down of the ankles can be seen on distance curves.

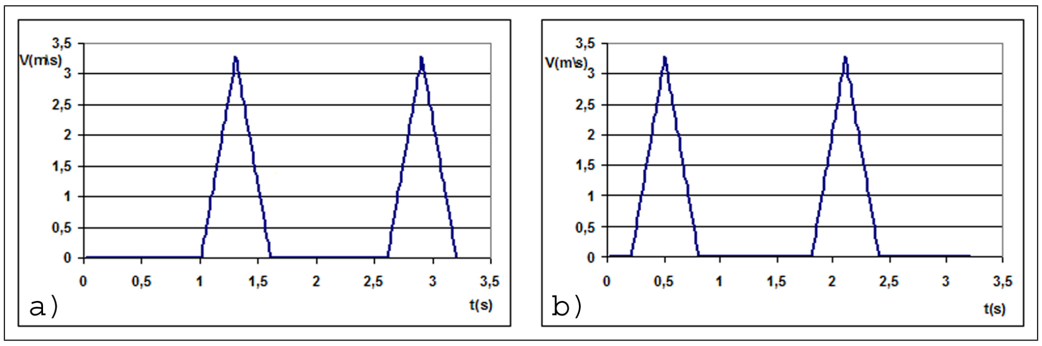


Figure 4.8: The velocity curve of a) left ankle and b) right ankle.

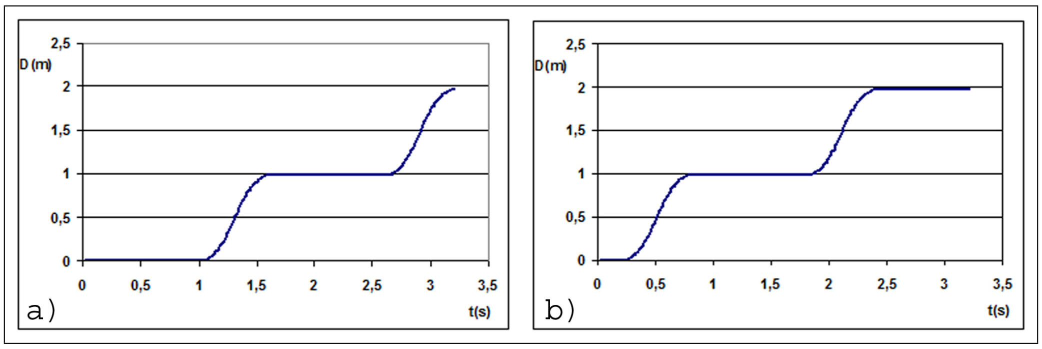


Figure 4.9: The distance curve of a) left ankle and b) right ankle.

In conclusion, a high-level walking motion is obtained in our system by using the parameters like walking speed, time elapsed during double support phase, and gait determinant parameters like pelvis rotation, pelvis tilt, and lateral displacement. Figures in Chapter 6.1 illustrate the obtained walking motion.

Chapter 5

IKAN

5.1 Motion of the Skeleton

Our system uses the kinematics based methods for motion control. Forward and inverse kinematics are two main approaches in kinematic animation. Our work focuses on the analytical inverse kinematics methods in which, the goal orientations are specified and the position or rotation of joints are computed by using analytical methods. Moving a hand to grab an object or placing the foot to a desired position requires the usage of inverse kinematics methods.

In our study, we used an inverse kinematics package, called IKAN. IKAN is a complete set of inverse kinematics algorithms for an anthropomorphic arm or leg. It uses a combination of analytic and numerical methods to solve generalized inverse kinematics problems including position, orientation, and aiming constraints. IKAN methodology is explained in [15].

IKAN provided us the required functionality to control the arm and leg of human model. For the arm, with the goal of putting the wrist in the desired location, IKAN computed the joint angles for the shoulder and elbow. In the case of leg, rotation angles for hip and knee is calculated.

IKAN's methodology is constructed on a 7 DOF fully revolute open kinematic chain with two spherical joints connected by a single revolute joint. Although the primary work is on the arm, the methods are suitable for a leg because, the kinematic chain of leg is similar to the kinematic chain of the arm. In the arm model, the spherical joints with 3 DOFs are shoulder and wrist; the revolute joint with 1 DOF is elbow. In the leg model, the spherical joints with 3 DOFs are hip and ankle; the revolute joint with 1 DOF is knee.

The details of how we incorporated IKAN with our work is as follows. Explaining the details for an arm will unravel the solution for the leg. Because, leg and arm are both considered being similar human arm-like (HAL) chains, only some parameters change in the case of leg.

First of all, the right-handed coordinate system illustrated in Figure 5.1 is assumed at all the joints (shoulder, elbow, and wrist in the case of the arm).

The elbow is considered as to be parallel to the length of the body at rest condition. The z-axis is from elbow to wrist. The y-axis is perpendicular to z-axis and it is the axis of rotation for elbow. The x-axis is pointing away from the body along the frontal plane of the body. The x, y, and z axes form a right-handed coordinate system.

Similar coordinate systems are assumed at the shoulder and at the wrist. The projection axis is always along the limb and the positive axis points away from the body perpendicular to the frontal plane of the body. The projection axis differs for left and right arm. Wrist to elbow and elbow to shoulder transformations are calculated since they are needed to initialize the `SRS` object in IKAN. The initialization process is as follows:

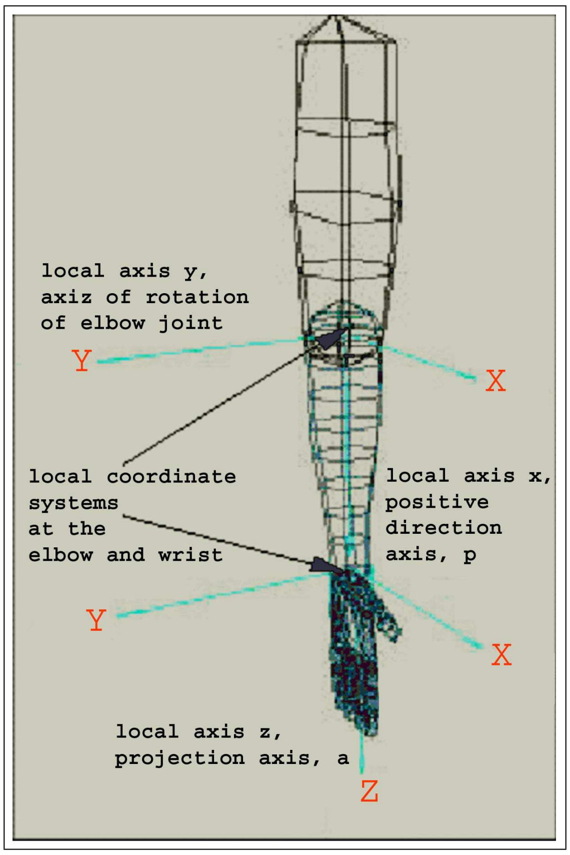


Figure 5.1: Example arm showing the selection of projection and positive axis (reprinted from [15]).

```
SRS ikSolver(T, S, a, p);
```

where `T` is the elbow to shoulder transformation matrix, `S` is the wrist to elbow transformation matrix, `a` is the projection axis, and `p` is the positive axis for the arm. z-axis and x-axis are used as parameters for projection axis and positive axis, respectively for the left HAL chains of left arm and left leg. Negative z-axis and x-axis are used as parameters for projection axis and positive axis, respectively for the right HAL chains of right arm and right leg.

5.2 Implementation Details

We reused the functionality provided in the C++ classes of `JackPlugin`, which is distributed in the IKAN package as an example source for the usage of basic `IK` classes. Actually, the classes of JackPlugin do not have a good object oriented structure. In that package the class `Limb` has the main functionality. We reused almost the whole functionality of the class Limb in our class `HALChain`. We stated a better object-oriented structure to take the advantage of object-oriented paradigm. C++ class structure, data encapsulation, inheritance, and polymorphism mechanism provided us much more cleaner and easier-to maintain code, and it allowed easier extensions. The class diagram in Figure 5.2 depicts the structure.

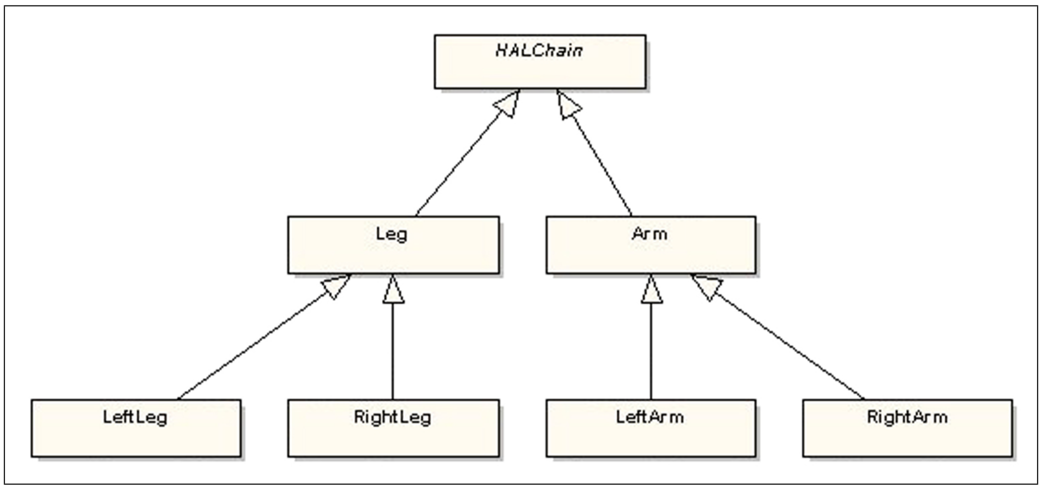


Figure 5.2: UML class diagram for IKAN classes that is used in our system.

The attributes and operations of the classes are given in Appendix B. The terms `R1-joint`, `R-joint`, `R2-joint` are used extensively. They are the joints in a HAL chain. In the case of the arm, `R1-joint` refers to shoulder where `R-joint` refers to the elbow and `R2-joint` refers to the ankle.

The arm is initialized with a Humanoid object and the name of the shoulder, elbow and wrist joints. In this initialization part, the transformation matrices (T and S) are computed and the inverse kinematics solver (`SRS` object) is initialized.

The methods `setGoalPos`, `solverJoint` are the main operations of the `HALChain` class. Call to the wrapper method `setGoalPos` is delegated to the functional class SRS. `setGoalPos` function sets the goal position for the end-effector. If the goal is feasible, the `swievel` angle of R-joint (elbow or knee) is calculated and the rotation matrix for the R-joint is computed using the swievel angle. Besides, if the upper and lower joint angle limits are specified, the valid angle ranges in which the R-joint can swievel is calculated. In `solveRJoint` method, the largest valid range is selected and the swievel angle, which is the middle value of this range, is used. Using this swievel angle value, the rotation matrix of R1-joint is computed by utilizing the SRS object's `solveR1` method. By the way, the position of the R-joint can be calculated by SRS's `AngleToPos` method, but it is not needed in our application, after the rotation matrices of R1 and R-joints appeared. Through this brief explanation it can be inferred that, the goal position is calculated relative to the R1-joint, because the R1-joint does not need to be static. Besides, after the rotation matrices are found, they need to be transformed into the global coordinate system. For example, in a inverse kinematics application such as walking animation, the pelvis and the ankle is always moving. There exists many goal positions. In each intermediate step, the goal position is first calculated relative to the pelvis. The orientation matrices of the pelvis and knee are calculated in local coordinate system. Then, they are transformed into the global coordinates.

The end-effectors positions and the orientations of joints can be seen in Figure 5.3. From the knowledge of end-effectors, the joint angles are found automatically.

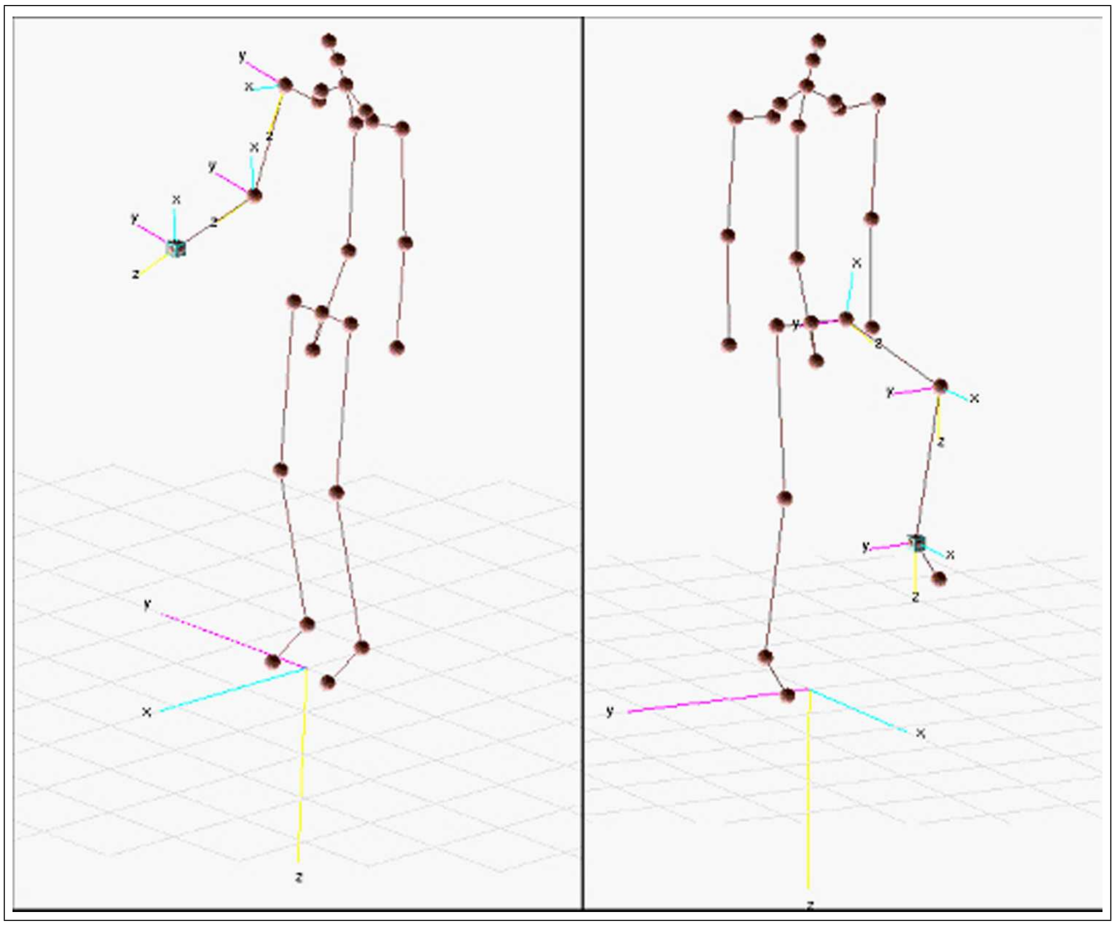


Figure 5.3: The joint orientations for the end-effector positioning for the right arm and the left foot.

Chapter 6

EXPERIMENTAL RESULTS

6.1 Visual Results

Figures 6.1, 6.2 and 6.3 illustrate the front, side and top views of the high-level walking behavior produced by our system.

The position curves seen in Figures 6.1, 6.2 and 6.3 are the trajectories of limbs, left ankle, right ankle and pelvis. These position curves and the velocity curves in Figures 4.8 of each limb are generated automatically by our system. The gait determinants compass gait, pelvic rotation, pelvic tilt, and lateral pelvic displacement are considered. Pelvis rotation is seen in Figure 6.1. Pelvic tilt can be seen in Figure 6.3. Lateral pelvic displacement and compass gait can be seen in Figures 6.2 and 6.3. Skinned human model walking behavior can be seen in Figure 6.4 [47].

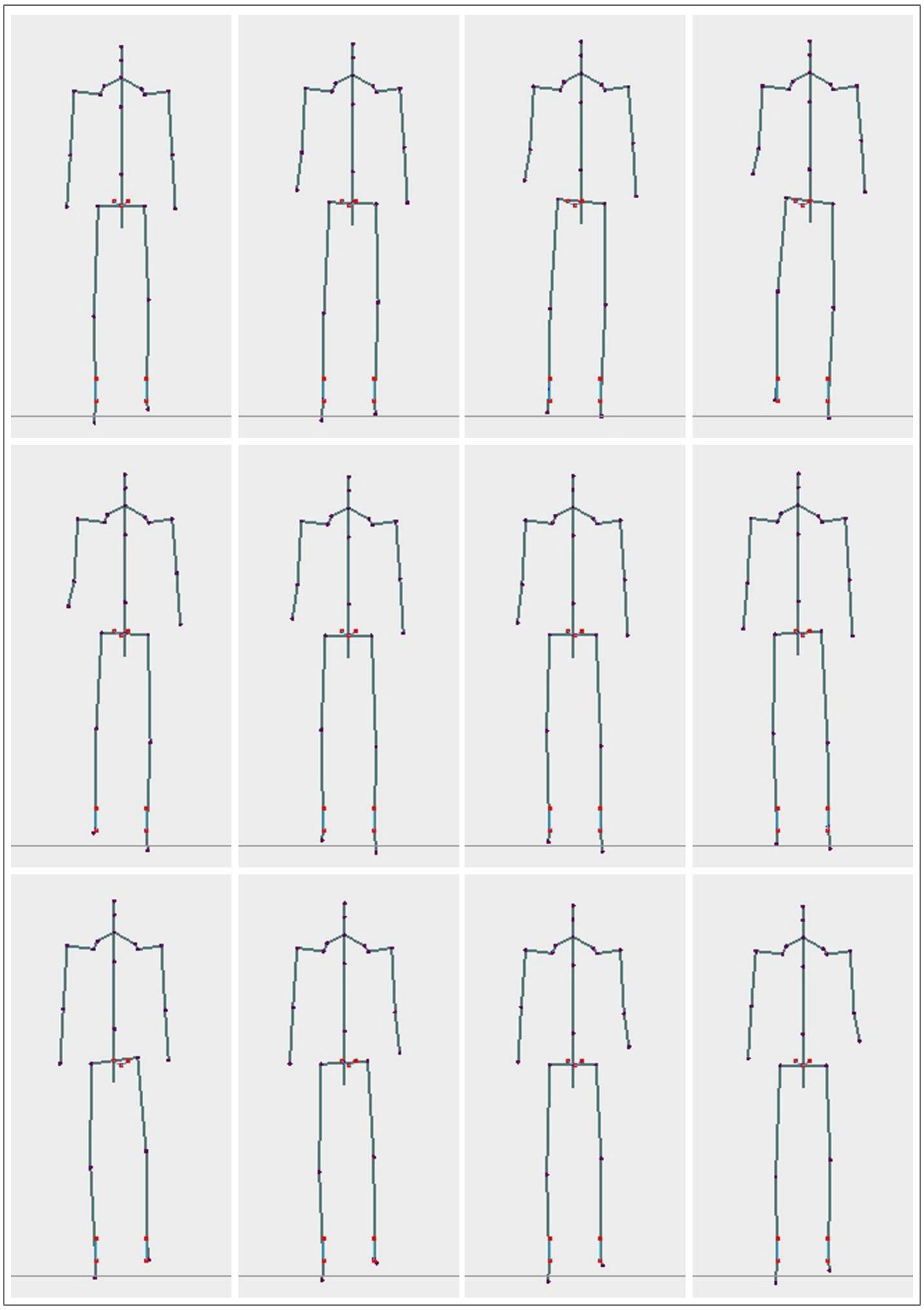


Figure 6.1: Front view of the walking articulated figure.

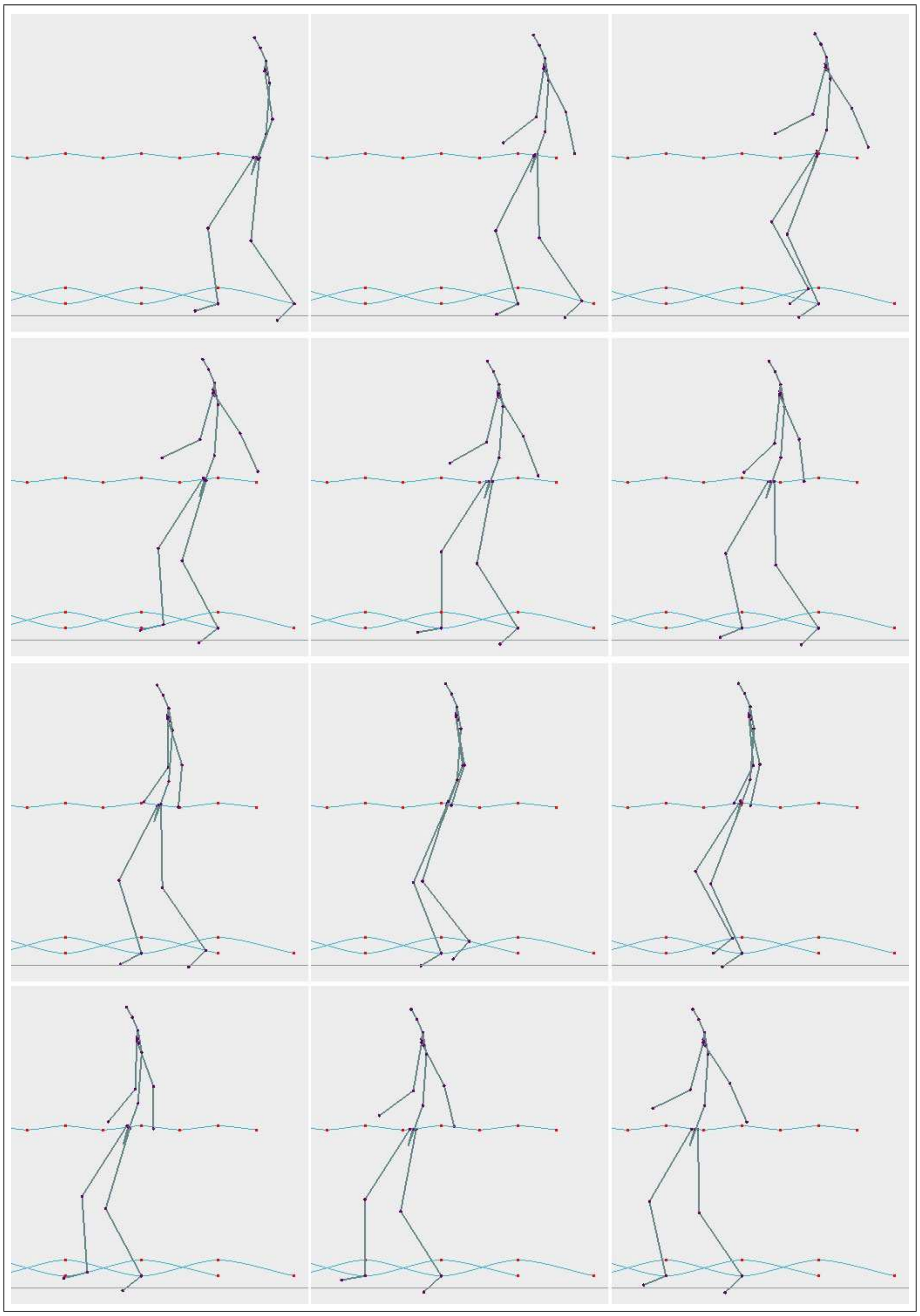


Figure 6.2: Side view of the walking articulated figure.

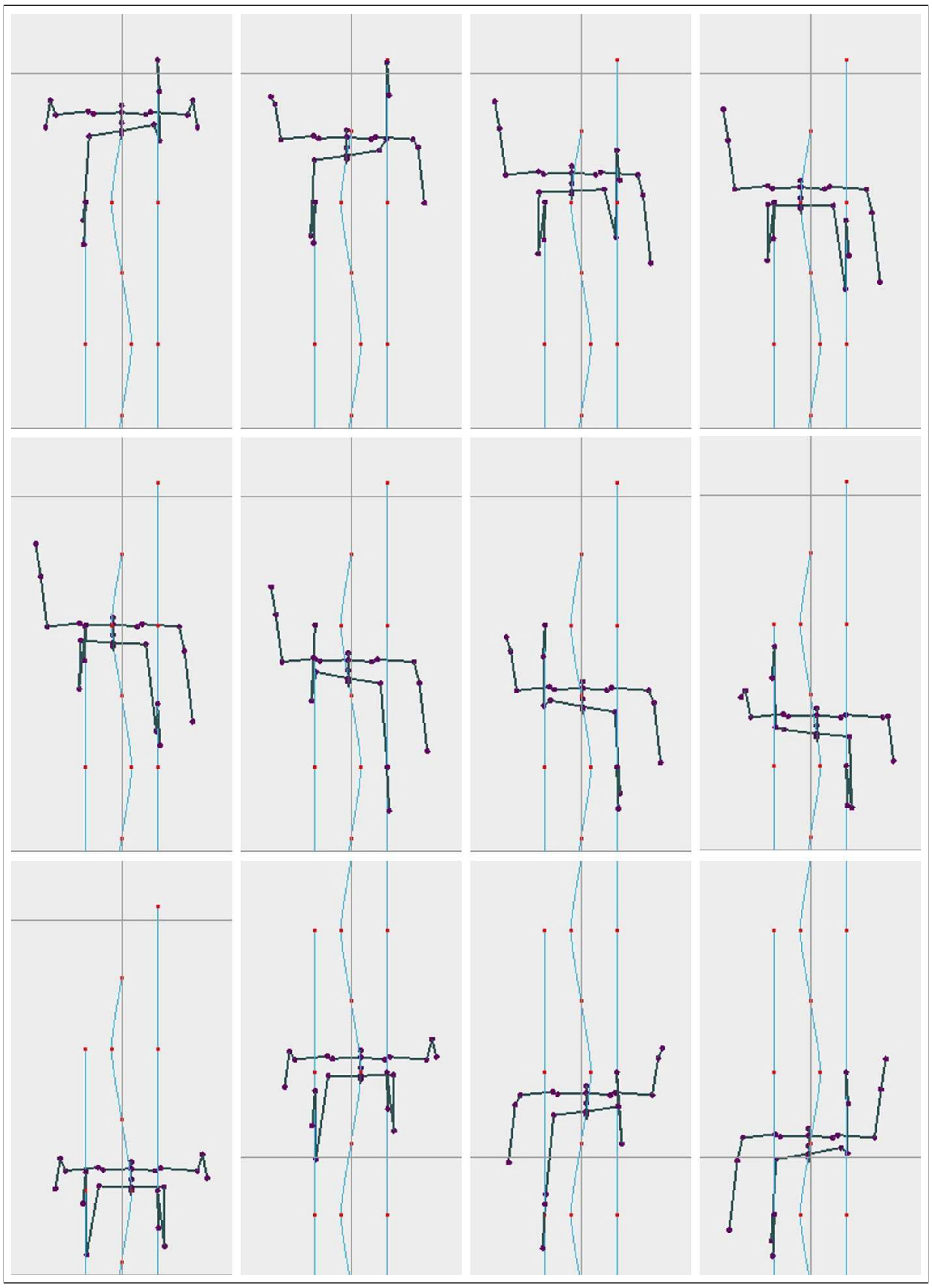


Figure 6.3: Top view of the walking articulated figure.

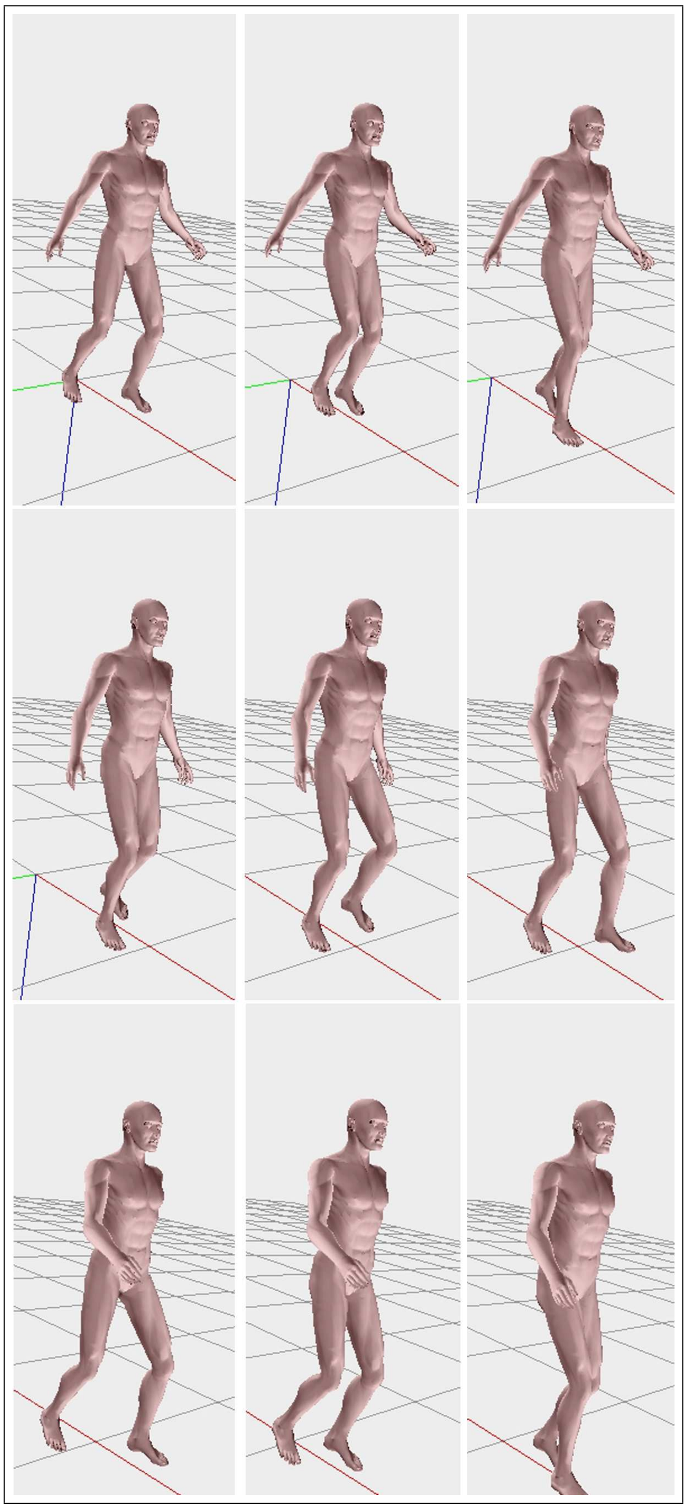


Figure 6.4: Skinned human model walking behavior.

Goal-directed motion of the arm and the leg of the articulated figure can be shown in Figures 6.5 and 6.6, respectively. The orientation of elbow (in case of arm) and knee (in case of leg) is computed by the inverse kinematics package IKAN.

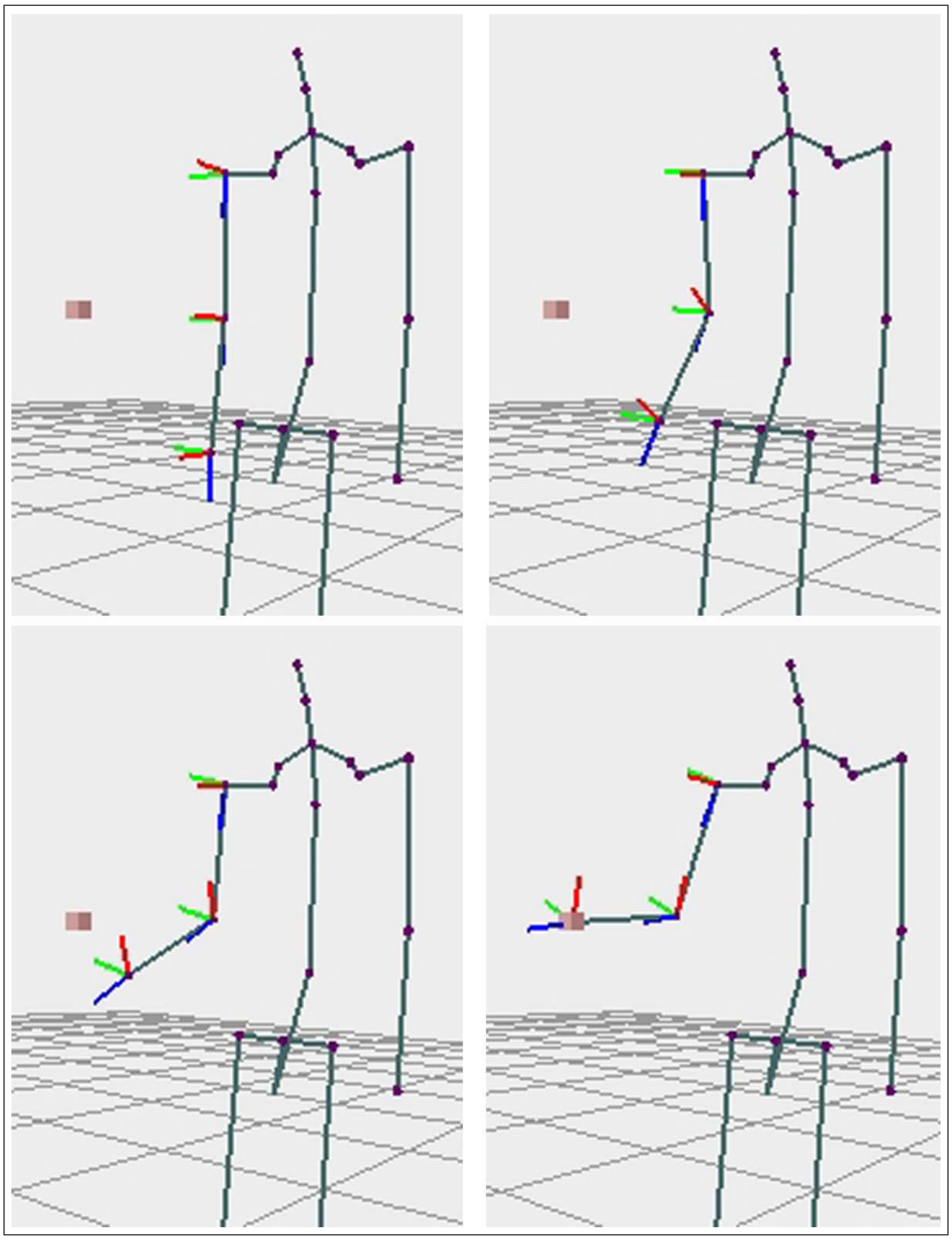


Figure 6.5: Goal-directed motion of the arm of the articulated figure.

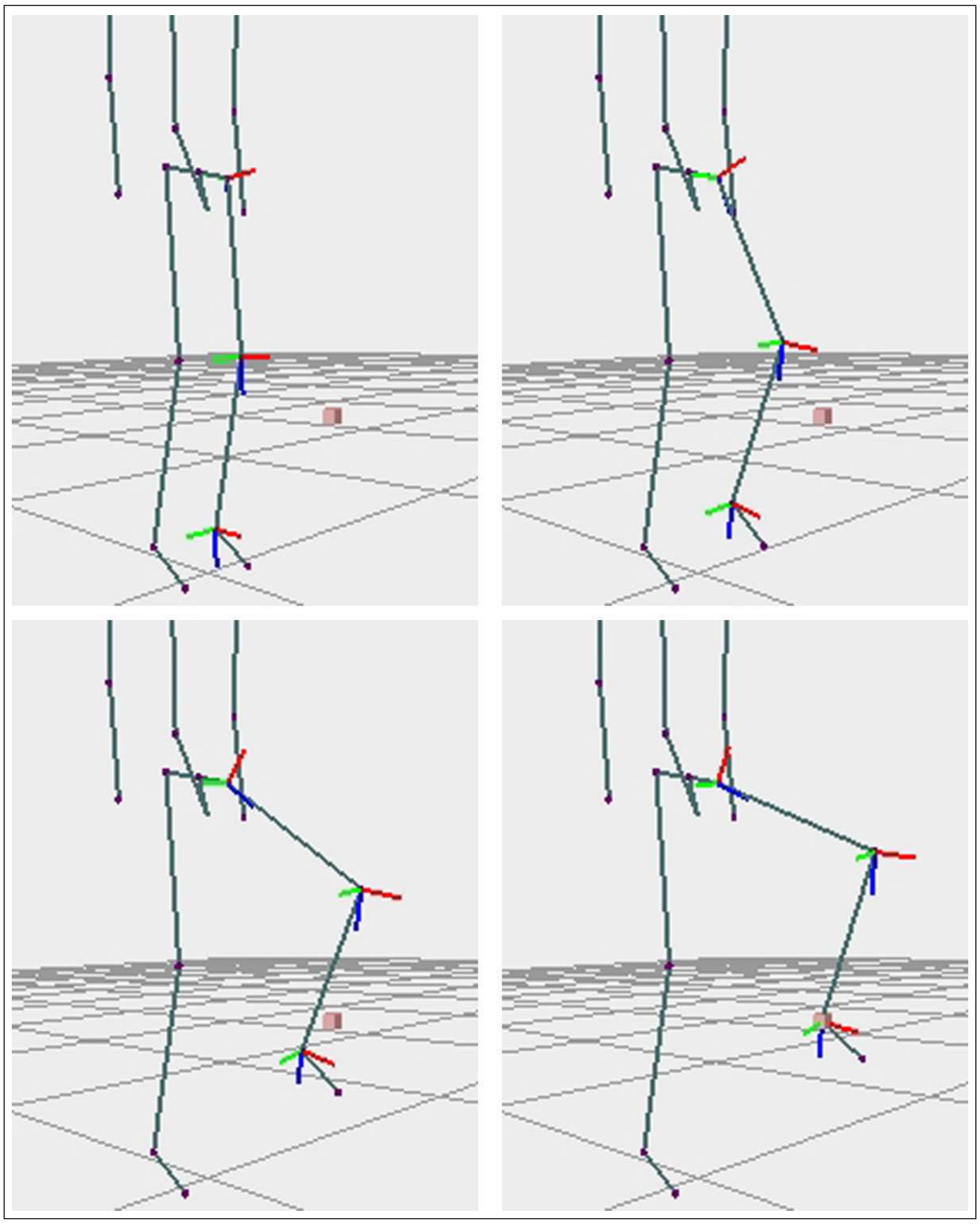


Figure 6.6: Goal-directed motion of the leg of the articulated figure.

6.2 Performance Analysis

We have successfully applied inverse kinematics algorithms for animating human walking, goal-directed motion and other user-defined motions of an articulated model. For this purpose we developed a user-friendly system. The major computation in our algorithms is the inverse kinematics method used in computing joint angles of the lower extremities. The IKAN Software is applied in our system to minimize the inverse kinematics computations. Since IKAN is based on a well designed, optimized and low level C library, it provides the required performance for solving inverse kinematic problems. Thus, real-time simulation can be easily achieved. We have tested our system on a Pentium-IV 1600 MHz (256 MB RAM) with 32MB Nvidia RIVA TNT2 graphics card and successfully computed a huge performance of an average of 397 frames/sec. The results also show that the computational complexity of the system is independent of how complex the motion is. However, some extra cost can be added when path planning is adopted to the system.

Chapter 7

CONCLUSION

This study introduces a motion control mechanism that works in a hierarchical manner and enables the user to generate different types of human motions in real-time. The system uses an articulated figure that is modeled based on the H-Anim 1.1 Specification.

At high level, the animator can produce basic locomotion by specifying some parameters, like locomotion velocity, size of walking step, the time elapsed during double-support, rotation, tilt, and lateral displacement of pelvis, and etc. These parameters are presented by paths that are generated based on piecewise cubic polynomial curves. These curves include some control points that allow the user to adjust the shape of the curve. At that point, we want to emphasize that defining the trajectories for limbs in a human figure for complex realistic motions is not an easy task. We generated these limb trajectories by observing the real human walking.

However, this high-level motion mechanism for walking requires low-level techniques. Actually, in this study most of the work is especially based on the low-level control of motion using kinematic methods. In this technique, motion characteristics of an object are specified by using splines. Spline curves provided the required functionality for the motion control of the articulated figure. They can be constructed with a few set of control points and can be manipulated easily. The paths for pelvis, ankle and wrist motions are specified using these spline curves. However, these curves only determine the positions of some joints. The motion of the whole articulated structure is generated by means of inverse kinematic techniques. IKAN software package, developed at the University of Pennsylvania, is utilized for this purpose. IKAN allowed us to easily control the arms and legs of our human figure.

As a result, by using these techniques realistic human motions can be successfully simulated in real time. In the system, there are some areas that needs further improvements. For example, more control parameters for high-level motions can be added in order to generate personalized human motions or motions with emotions like “walking happily”, “walking sad”. Besides, sophisticated motion planning and path generation mechanisms can be adopted to generate motions in an environment with obstacles. Another possible improvement of our system is to integrate the kinematics methods with dynamics methods. Using two approaches we can simulate more realistic animations. For example, we can animate a heavily loaded human while walking up the stairs. Besides, a model walking in water or through a strong wind can be realistically modelled by this hybrid method.

Appendix A

HUMAN MODEL IN XML FORMAT

A.1 Document Type Definition (DTD) of Human Model

```
<!ELEMENT Humanoid (author, name, center, Joint*)>
<!ELEMENT author (#PCDATA)>
<!ELEMENT name (#PCDATA)>
<!ELEMENT center (#PCDATA)>
<!ATTLIST center value CDATA #REQUIRED>
<!ELEMENT Joint (Joint*, Segment*, Site*)>
<!ATTLIST Joint name CDATA #REQUIRED>
<!ATTLIST Joint center CDATA #REQUIRED>
<!ATTLIST Joint limitx CDATA #IMPLIED>
<!ATTLIST Joint limity CDATA #IMPLIED>
<!ATTLIST Joint limitz CDATA #IMPLIED>
<!ELEMENT Segment EMPTY>
```

```
<!ATTLIST Segment name CDATA #REQUIRED>
<!ATTLIST Segment mass CDATA #IMPLIED>
<!ELEMENT Site EMPTY>
<!ATTLIST Site center CDATA #REQUIRED>
<!ATTLIST Site name CDATA #REQUIRED>
```

A.2 XML Formatted Data of Human Model

```
<?xml version="1.0" ?>
<Humanoid>
  <author>Aydemir Memisoglu</author>
  <name>Little</name>
  <center value="0.0000 0.0000 0.0000" />
  <Joint name="HumanoidRoot" center="0.1296 0.0000 -3.8563">
   <Joint name="sacroiliac" center="0.0075 0.0000 -4.2920">
     <Joint name="l_hip" center="-0.0005 -0.4446 -4.2920"
     limitx="-1.00 2.00" limity="-1.40 2.90"
     limitz="-1.40 1.30">
       <Joint name="l_knee" center="0.1441 -0.4446 -2.2778"
       limity="-3.00 0.00">
         <Joint name="l_ankle" center="-0.3444 -0.4446 -0.3070">
           <Joint name="l_midtarsal" center="0.1722 -0.4446 -0.0005"/>
         </Joint>
       </Joint>
     </Joint>
     <Joint name="r_hip" center="0.0136 0.4446 -4.2920"
     limitx="-1.00 2.00" limity="-1.40 2.90"
     limitz="-1.40 1.30">
       <Joint name="r_knee" center="0.1488 0.4446 -2.2993"
```

```
    limity="-3.00 0.00">
      <Joint name="r_ankle" center="-0.3585 0.4446 -0.3332">
        <Joint name="r_midtarsal" center="0.1722 0.4446
        0.0000" />
      </Joint>
    </Joint>
  </Joint>
</Joint>
<Joint name="vl5" center="-0.3632 -0.0000 -4.8458">
  <Joint name="vt6" center="-0.3744 -0.0000 -6.2893">
    <Joint name="vt1" center="-0.2811 -0.0000 -6.7971">
      <Joint name="vc4" center="-0.1393 -0.0000 -7.1298">
        <Joint name="skullbase" center="0.0104 -0.0000
        -7.3858" />
      </Joint>
      <Joint name="r_sternoclavicular" center="-0.2544 0.3248
      -6.6328">
        <Joint name="r_acromioclavicular" center="-0.2877 0.3912
        -6.4830">
          <Joint name="r_shoulder" center="-0.2521 0.8925 -6.5425"
          limitx="-1.00 3.00" limity="-1.70 3.10"
          limitz="-1.00 1.30">
            <Joint name="r_elbow" center="-0.5892 1.9601 -6.3165"
            limity="0.00 3.00">
              <Joint name="r_wrist" center="-0.2611 2.9274
              -6.1421"/>
            </Joint>
          </Joint>
        </Joint>
```

```
     </Joint>
     <Joint name="l_sternoclavicular" center="-0.2652 -0.3838
     -6.5804">
      <Joint name="l_acromioclavicular" center="-0.2984 -0.4502
      -6.4779">
       <Joint name="l_shoulder" center="-0.2811 -0.9496 -6.5280"
       limitx="-1.00 3.00" limity="-1.70 3.10"
       limitz="-1.00 1.30">
        <Joint name="l_elbow" center="-0.4192 -0.9426 -5.1151"
        limity="0.00 3.00">
         <Joint name="l_wrist" center="-0.3728 -0.9285 -3.8543"/>
        </Joint>
       </Joint>
      </Joint>
     </Joint>
    </Joint>
   </Joint>
  </Joint>
 </Joint>
</Humanoid>
```

Appendix B

CLASS DIAGRAMS

B.1 Hbody Package

class **Humanoid**

This class serves as a container for the Joint, Segment, and Site nodes. After constructing a Humanoid object, the programmer refers the joints using the public methods if this class.

Attribute	**Type**	**Notes**
joints	protected: vector<Node*>	container for Joint nodes
segments	protected: vector<Node*>	container for Segment nodes
sites	protected: vector<Node*>	container for Site nodes
humanoidRoot	protected: Node*	root node

Table B.1: Humanoid attributes

Method	**Type**	**Notes**
Humanoid ()	public:	constructor
getRoot ()	public: Node*	returns the root Node
getNodeByName (char*)	public: Node*	returns the Node with the given name
setRelTransform ToParents ()	public: void	traverse the node hierarchy and set the relative transformation matrix of nodes according to their parent nodes
saveToXMLFile(char*)	public: void	save the structure of the humanoid to a file in XML format
loadXMLFile(char*)	public: void	parse the given XML file and construct a humanoid structure
draw (int)	public abstract: void	display the humanoid using the OpenGL API with given properties
...		

Table B.2: Humanoid methods

class **Node**

Node is the base class for other classes Joint, Segment, and Site. It serves as a node in the humanoid tree structured hierarchy and provides the basic functionality like identification, positioning, accessing parent and child nodes.

Attribute	**Type**	**Notes**
type	protected: NodeType	type of the Node (Joint, Segment, or Site)
name	protected: char	name of the Node
parent	protected: Node*	pointer to the parent Node
children	protected: vector<Node*>	container for the children of the Node
matrix	protected: Matrix4&	global matrix of the Node used for positioning and orientation

Table B.3: Node attributes

Method	**Type**	**Notes**
Node (NodeType, char*, Vector3&)	public:	construct a Node object with given type and name at specified position
getName ()	public const: char*	get the name of the Node
getType ()	public: NodeType	get type of the Node
addChildren (Node*)	public abstract: void	add a child Node to the Node
getChildren ()	public abstract: vector<Node*>&	get the children of the Node
removeChildren (Node*)	public abstract: void	remove the specified child Node
setParent (Node*)	public: void	set the parent of this Node
getParent ()	public: Node*	get a pointer to the parent Node
getGlobal ()	public: mlMatrix4&	get global matrix of the Node
setGlobal ()	public: mlMatrix4&	set global matrix of the Node
...		

Table B.4: Node methods

class **Joint**

Extends: Node

This class is the main node in the hierarchy of the Humanoid structure. Upper and lower limits for the joint angles on axis x, y, z can be determined. Because it inherits from Node, it also uses the functionality of class Node.

Attribute	**Type**	**Notes**
ulimit	protected: float[3]	upper limits for the joint angles
llimit	protected: float[3]	lower limits for the joint angles

Table B.5: Joint attributes

Method	Type	Notes
Joint (char*, Vector3&)	public:	construct a Joint object with given name at specified position
updateChildren Globals ()	public abstract: void	update the global matrix of children according to their relative transformation matrix
setLimits (Joint::Axis, float,float)	public abstract: void	set the lower upper limits for the specified axis
getUpperLimit (Joint::Axis)	public abstract: float	get the upper limit angle for the given axis (in radian)
getLowerLimit (Joint::Axis)	public abstract: float	get the lower limit angle for the given axis (in radian)
hasLimit (Joint::Axis)	public abstract: bool	return true if joint has limits for the given axis

Table B.6: Joint methods

class **Segment**

Segment class is used to define the segments in human body structure. It has a bounding box and mass. The has simple functionality with get and set methods for the bounding box and mass information of the Segment. It has also the functionality of the class Node.
Extends: Node

Attribute	Type	Notes
bboxCenter	protected: Vector3	bounding box center
bboxSize	protected: Vector3	bounding box dimensions
centerOfMass	protected: Vector3	center of mass of the Segment
mass	protected: float	mass of the Segment

Table B.7: Segment attributes

Method	Type	Notes
Segment (char*, Vector3&, Vector3&, Vector3&, float)	public:	construct a Segment object with given name, bounding box, and mass information
...		

Table B.8: Segment methods

class **Site**

Site class is used to represent the Site nodes in Humanoid structure. It has also the functionality of the class Node.
Extends: Node

Method	**Type**	**Notes**
Site (char*, Vector3&)	public:	construct a Site node with given name at specified position
...		

Table B.9: Site methods

B.2 HBodyIK Package

class **HALChain**

HALChain is an abstract class which provides almost all the functionality for the inverse kinematics solution of a human arm like chain. The class has the functionality of the class Limb used in JackPlugin software. The internal methods of the class are not listed. It uses the main IKAN class SRS to solve the positional goals for end-effectors wrist in case of arm and ankle in case of leg.

Attribute	**Type**	**Notes**
ikSolver	protected: SRS	the main IKAN SRS object to solve the inverse kinematics problem
...		

Table B.10: HALChain attributes

Method	**Type**	**Notes**
HALChain()	public:	construct a HALChain object
setGoal (Matrix4&)	public abstract: int	set the goal position for the end-effector of the chain
solveRJoint ()	public : void	find the orientation for the R joint, elbow (in case of arm) or knee (in case of leg)

Table B.11: HALChain methods

class **Arm**

Arm class has the functionality of the class HALChain. Given a position goal for the end-effector wrist joint, it computes the orientation of shoulder and elbow joints. It has also simple set and get methods to access the shoulder, elbow, and wrist joints and relative transformation matrices. The classes LeftArm and RightArm, the attributes and functionality of which are not listed, are simple Arm classes with different projection axis, and positive direction axis.
Extends: HALChain

Attribute	**Type**	**Notes**
shoulder	protected: Joint*	pointer to shoulder Joint
elbow	protected: Joint*	pointer to elbow Joint
wrist	protected: Joint*	pointer to wrist Joint
elbowToShoulder	protected: mlMatrix4	elbow to shoulder transformation
wristToElbow	protected: mlMatrix4	wrist to elbow transformation

Table B.12: Arm attributes

Method	**Type**	**Notes**
Arm ()	public:	construct an Arm object
init (Humanoid*, char*, char*, char*)	public: void	initialize the Arm object and set the Humanoid and joint names for shoulder, elbow, and wrist
getProjection Axis()	public abstract const: float*	get the projection axis for the arm
getPositive DirectionAxis()	public abstract const: float*	get the projection axis for the arm
setGoal(Vector3&)	public: int	set a goal position for the wrist joint
...		

Table B.13: Arm methods

class **Leg**

Arm class has the functionality of the class HALChain. Given a position goal for the end-effector ankle joint, it computes the orientation of hip and knee joints. It has also simple set and get methods to access the hip, knee, and ankle joints and relative transformation matrices. The classes LeftLeg and RightLeg, the attributes and functionality of which are not listed, are simple Leg classes with different projection axis, and positive direction axis.
Extends: HALChain

Attribute	**Type**	**Notes**
hip	protected: Joint*	pointer to hip joint
knee	protected: Joint*	pointer to knee joint
ankle	protected: Joint*	pointer to ankle joint
kneeToHip	protected: mlMatrix4	knee to hip transformation
ankleToKnee	protected: mlMatrix4	ankle to knee transformation

Table B.14: Leg attributes

Method	**Type**	**Notes**
Leg ()	public:	construct an Leg object
init(Humanoid*, char*, char*, char*)	public: void	initialize the Leg object and set the Humanoid and joint names for hip, knee, and ankle
getProjection Axis()	public abstract const: float*	get the projection axis for the leg
getPositive DirectionAxis()	public abstract const: float*	get the projection axis for the leg
setGoal (Matrix4&)	public: int	set a goal position for the ankle joint
..		

Table B.15: Leg methods

B.3 Curve Package

class **Curve**

Curve class is the base class to represent the cubic splines and straight lines. The classes CubicSpline and Line inherits from this class. Curve class has also some methods to rotate, move all of the control points.

Attribute	**Type**	**Notes**
knots	protected: vector<Vector3>	knots (control points) of the curve

Table B.16: Curve Attributes

Method	Type	Notes
Curve (vector<Vector3>&)	public:	construct a Curve object with given knots
eval (float)	pure public abstract: Vector3	given parameter u, return the position
getLength ()	pure public abstract: float	get length of the curve
getLength (int, int)	pure public abstract: float	get length of the curve between given knots
arcLength (float)	pure public abstract: Vector3	given the distance travelled along curve, return the position
getKnots ()	public: vector<Vector3>&	return the vector of knots
insertKnot (int, Vector3&)	public: void	inserts a knot at specified index
addKnot (Vector3&)	public: void	adds a knot to the end
draw ()	public abstract: void	display curve using OpenGL API
...		

Table B.17: Curve Methods

class **CubicSpline**

This class is the base class to represent the cubic splines. Cardinal spline is a type of cubic spline.
Extends: Curve

Attribute	Type	Notes
basisMatrix	protected: Matrix4	basis Matrix which is needed to compute the points of curve
numOfGrains	protected: int	number of grains of the CubicSpline

Table B.18: CubicSpline Attributes

Method	Type	Notes
CubicSpline (vector<Vector3>, int)	public:	construct a CubicSpline object with given knots and parameter number of grains
...		

Table B.19: CubicSpline Methods

class **CardinalSpline**

This class is used to represent the Cardinal splines. Cardinal splines are used to as position, distance and orientation (rotation about axis x, y, z) curves in our human motion control system. CardinalSpline class is a concrete class, so the abstract methods of the base classes CubicSpline, and Curve like arcLength, getLength, etc. are implemented.
Extends: CubicSpline

Attribute	Type	Notes
tension	protected: float	tension parameter of the spline

Table B.20: CardinalSpline Attributes

Method	Type	Notes
CardinalSpline (vector<Vector3>, int, float)	public:	construct a CardinalSpline object from the given vector of knots, and parameters number of grains and tension
eval (float)	public: Vector3	given the parameter u, return the position
getLength ()	public: float	get length of the curve
getLength (int, int)	public: float	get length of the curve between given knots
arcLength (*float*)	public: Vector3	given the distance travelled along curve, return the position
draw ()	public : void	display curve using OpenGL API
...		

Table B.21: CardinalSpline Methods

class **Line**
This class is used to represent straight lines. Lines are used to represent the velocity curves of ankles and pelvis in our system to control human walking. Line is a concrete class, so the abstract methods of the base class Curve like arcLength, getLength, etc. are implemented.
Extends: Curve

Method	**Type**	**Notes**
Line (vector<Vector3>)	public:	construct a line from the given knots
eval (float)	public: Vector3	given the parameter u, return the position
getLength ()	public: float	get length of the line
getLength (int, int)	public: float	get length of the line between given knots
arcLength (float)	public: Vector3	given the distance travelled along line, return the position
...		

Table B.22: Line Methods

Appendix C

THE SYSTEM AT WORK

In this part we introduce the user interface and functionality of our system. The system is implemented by Aydemir Memişoğlu and Mehmet Şahin Yeşil [47]. Motion control part is implemented by Aydemir Memişoğlu using inverse kinematics based on analytical methods. Realistic rendering using a multi-layered human model that consists of skeleton, muscles and skin is implemented by Mehmet Şahin Yeşil.

C.1 Overview

Our application is Single Document Interface (SDI) application implemented using Visual C++ 6.0 and Microsoft Foundation Classes (MFC). The graphics display API OpenGL is used. The top level user interface of the system is seen in Figure C.1. The elements on the interface can be mainly divided into four parts:

- *The Main Menu:* This consists of menu bar and toolbar. It basically allows the user to control the application.

- *The Motion Control Toolbox:* This toolbox allows user to control the skeleton and and generate new motions. It consists of two panels: Skeleton and Motion.

- *The Keyframe Editor:* This editor allows user to generate curves for distance, joint angles in order to characterize the motion of the articulated figure.

- *The Viewing Area:* The viewing area has quad view layout with the front, top, side, and perspective views of the 3D environment.

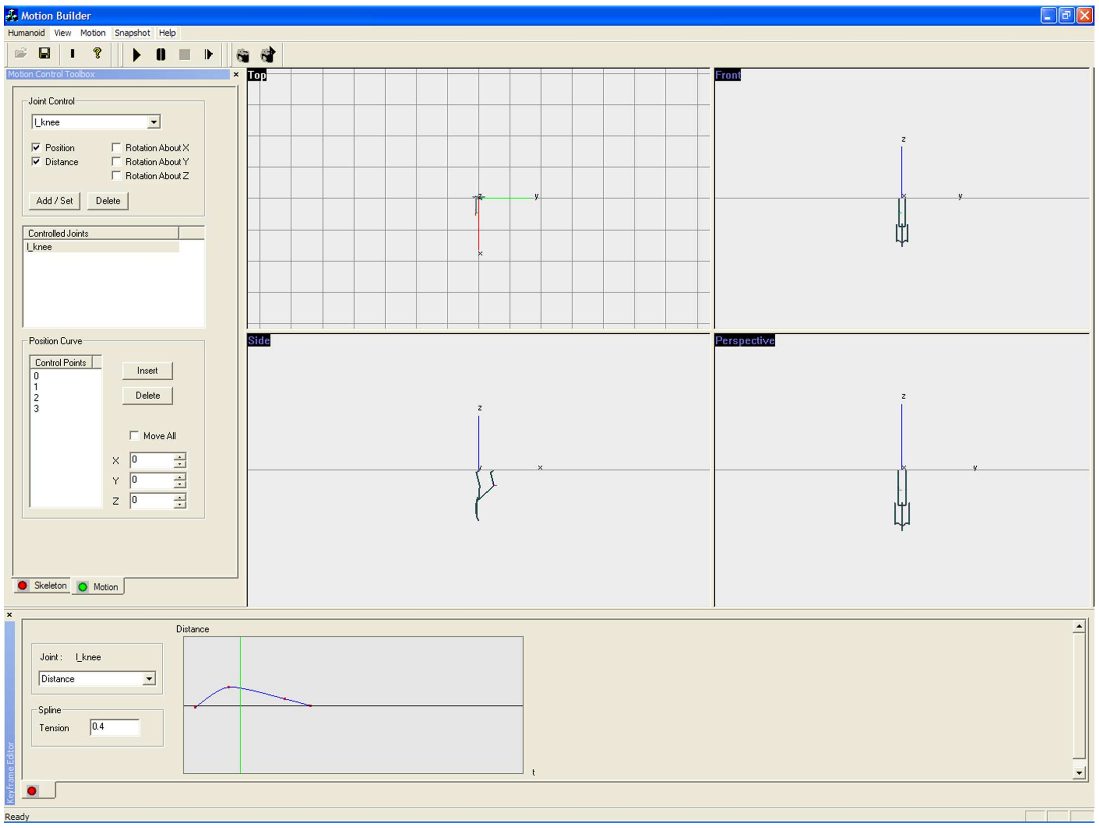


Figure C.1: Top level user interface of the system.

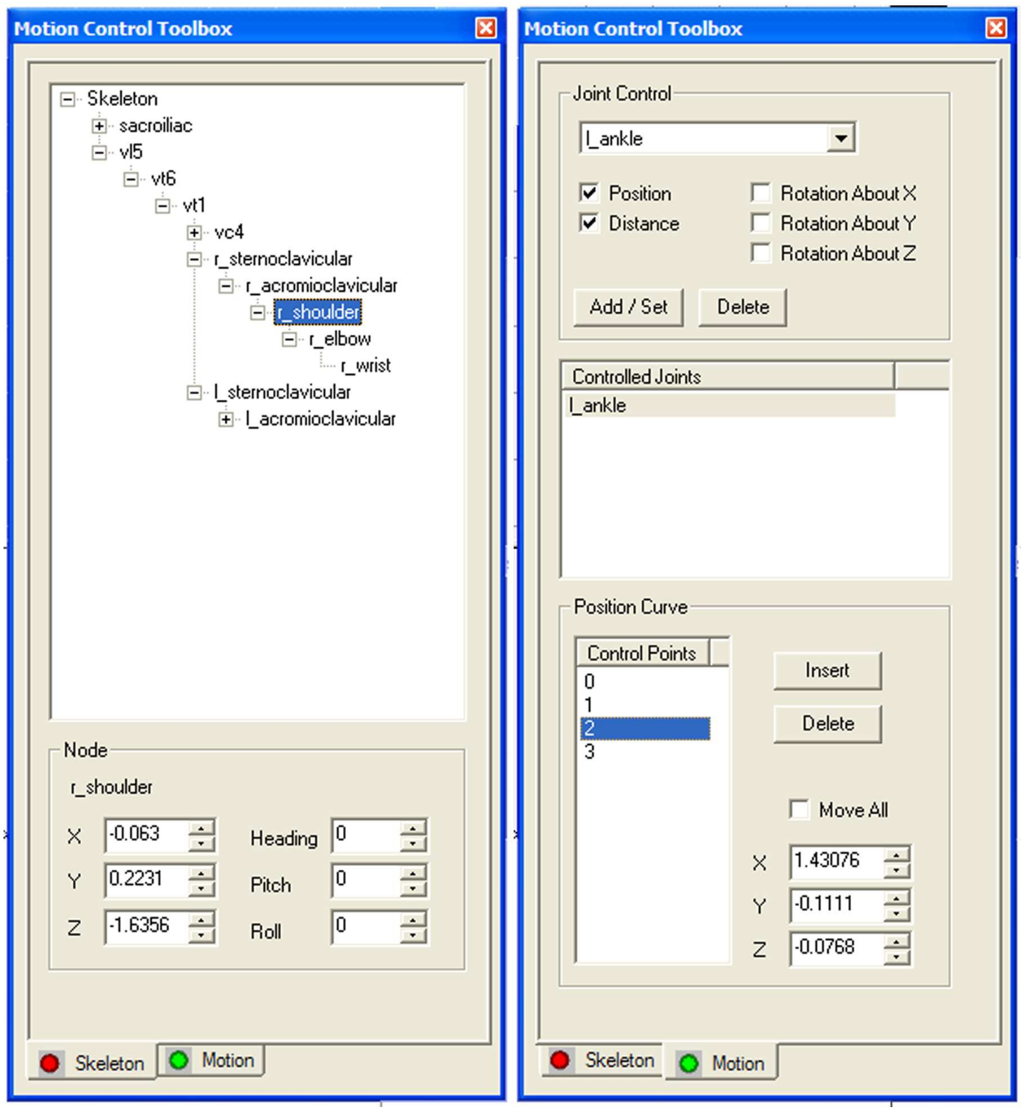
C.1.1 The Main Menu

The main menu part of the program consists of the menu bar and the other toolbars. The menu bar includes “File”, “View”, “Motion”, “Snapshot” and “Help” subitems and provides the general functionalities like creating and opening an object model, changing the user interface options, and creating a new motion or loading an existing one. The user also can start, stop, pause and step by step play the loaded animation by using the toolbar. The “Snapshot” menu item and the toolbar gives user the opportunity to take the snapshots of the animation.

C.1.2 The Motion Control Toolbox

Motion control toolbox includes two panels (see Figure C.2). The first panel, skeleton panel contains skeletal information of the articulated figure. On the upper part of the panel, the hierarchical structure of the skeleton is illustrated in a MFC tree control. The node part of the panel shows the position and orientation information of the selected joint. These values of the joint can also be modified by the user and the changes will be directly adopted to the figure on the viewing area.

On the other hand, the motion panel of the motion control toolbox allows the user to make modifications on the position curves of the end-effector (ankles and wrists) and root joints of the structure. These modification results with different types of motion. The upper part of the motion panel enables the user to select the desired joint, and types of control for a joint. The user can add and delete joint to control or update the types of control for the selected controlled joint by using ‘Add / Set’ and ‘Delete’ buttons. Selected joints will be listed on the ‘controlled joints’ listbox and the position curve of the joint will be also drawn on the viewing area. Properties of the position curve of the selected joint can be seen on the position curve part of the panel. These properties are mainly



Node: r_shoulder
X -0.063 Heading 0
Y 0.2231 Pitch 0
Z -1.6356 Roll 0

Joint Control: l_ankle
[✓] Position [ ] Rotation About X
[✓] Distance [ ] Rotation About Y
[ ] Rotation About Z

Controlled Joints: l_ankle

Control Points: 0, 1, 2, 3 (2 selected)
[ ] Move All
X 1.43076
Y -0.1111
Z -0.0768

Figure C.2: The motion control toolbox

denoted by the control points. The user can either change the position of an existing control point or insert a new one. All these impacts will directly affect the figure drawn on the viewing area.

C.1.3 The Keyframe Editor

Keyframe editor toolbox will be displayed for a selected joint when one of the controlled joints is double-clicked. While the motion panel includes the controls for manipulating the position curve of a joint, the keyframe editor provides the functionality for editing the distance and orientation curves of the joint. The distance curve specifies the distance travelled over time. The rotation curves specify the rotations about x, y, and z axes applied over time. The editor will only include the curves that are selected in the motion panel. As it is seen on Figure C.3, the keyframe editor wants you to select the curve to be edited. When the curve is selected, it will be drawn on the right frame of the editor. The curve can be edited at this frame by changing the positions of the control points and the changes can be followed on the viewing area. New control points can be added using the right mouse button and holding the ctrl key. Control points can be deleted using right mouse button and holding the ctrl key. A green line, which can be positioned along the x-axis (axis representing time), enables the user to examine the pose of articulated figure at specified time. This enables the user to interactively manipulate the curve and see the effects at any time by positioning the green line on x-axis using mouse. The user can also set the tension parameter of the curves which are Cardinal splines. All these functionalities provide the opportunity to create different motions easily.

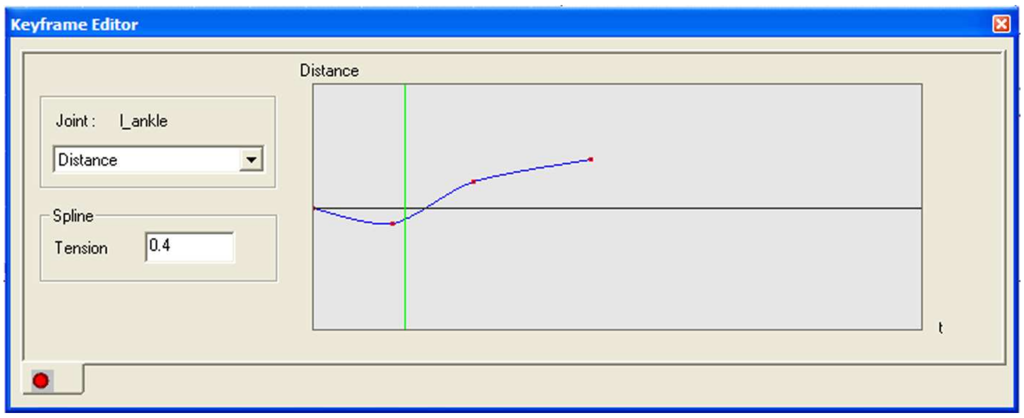


Figure C.3: The keyframe editor

C.1.4 The Viewing Area

The viewing area of the system includes four view layout; top, front, side, and perspective (see Figure C.4). The user can either select and view one of the layouts or use all of them. Zooming and view point change operations can be performed in each frame by using mouse and keyboard keys. Using left mouse button and holding the ctrl key, the user can rotate the figure in 3D space. The figure can be translated using the right mouse button and holding the ctrl key. Zooming can be done using just the right mouse button.

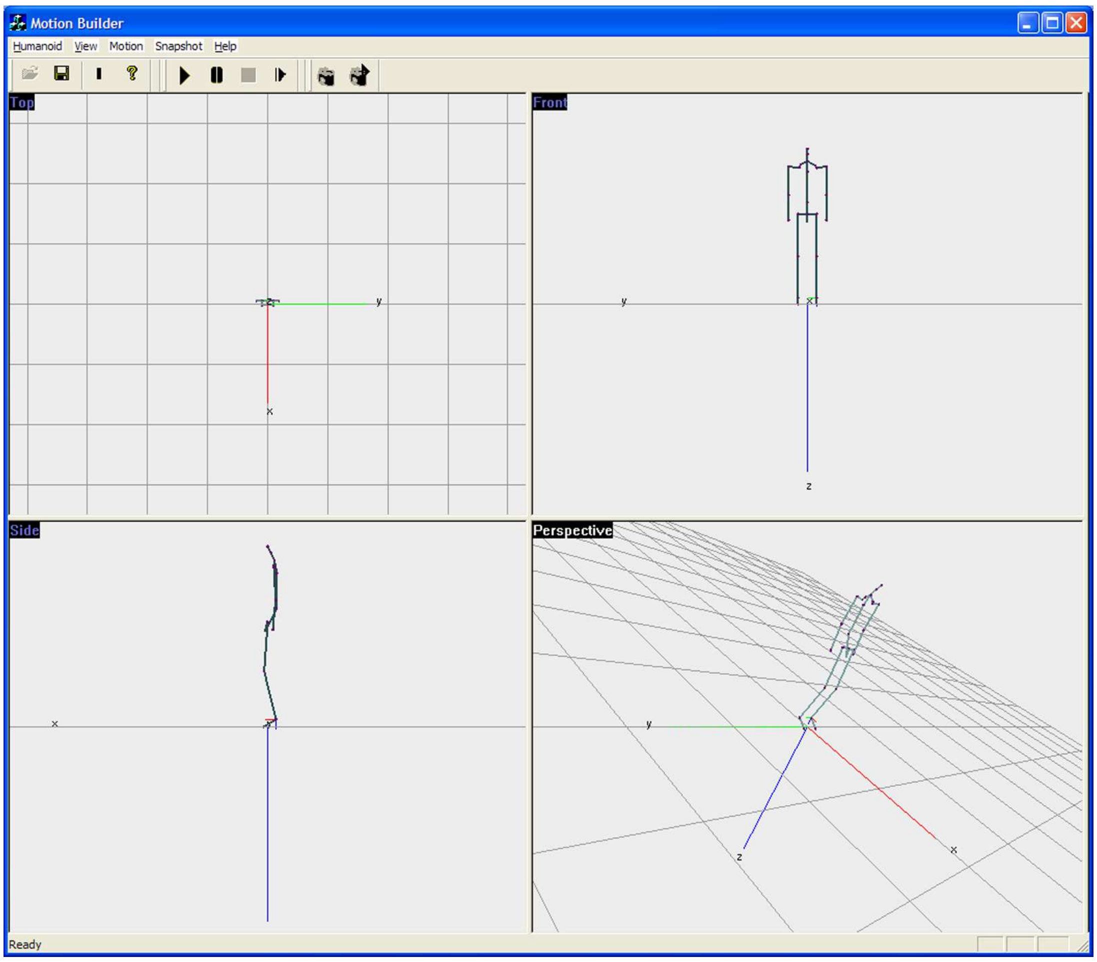


Figure C.4: The viewing area

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