High Controllability and Automaticity for Physically-based Animation of Brachiation

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Abstract

Brachiation is a sequence of fascinating and sophisticated movements employed by primates to use alternating bimanual support to swing beneath one overhead hold to another by applying appropriate forces and torques. In nature, there are many kinds of species of primate that can perform various varieties of brachiations, the most famous experts are Hylobates, a family of primate, which contains two categories: siamangs and gibbons. The control methodology of brachiation has not been explored in the scope of computer animation, especially in physically-based computer animation control.

This work deals with the animation and control of brachiation based on two new concepts defined in this thesis, automaticity and controllability. Controllability is to evaluate the input ability of an animation system and how it is able to precisely understand the animator's anticipation and follow this anticipation to interactively generate appropriate animation. Automaticity is to judge the output capability of an animation system and how it is able to automatically generate animation with minimal intervention from the animator. Controllability and automaticity are regarded as two of the most important measurements in this study to analyze and evaluate the existing animation methodologies. Based on this analysis, a brachiation system with high controllability and high automaticity is devised.

Four contributions towards achieving brachiation control are presented after comprehensively studying the Hylobates' brachiation and developing appropriate dynamic models of appropriate complexity. The first contribution, that of a high controllability and physically-based brachiation control, is a novel low-level interactive control. The second and third contributions consist of two high automaticity brachiation controls, a middle-level tailored control based on limited phase control and a high-level heuristic control based on learning control theory. They are shown to be useful no matter whether the modelling of the Hylobates' brachiation is simple or complex. The fourth contribution is integrative control. This is the first time this control structure has been depicted. It synthesizes controllability and automaticity by integrating low-level interactive control with middle-level tailored control and high-level heuristic control respectively. This control structure reveals that sophisticated integrative control possesses high controllability as well as high automaticity. It is a versatile technique to animate various satisfactory brachiation animations.

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Contents

List of Figures

List of Tables

Chapter 1

Introduction

When we wish to accomplish animation, it is natural and unavoidable to face three essential factors, the $3As$: Animator, Animation result, and Animation system. An animation system consists of equipment, methods, the character as well as goal motion sequence, as shown in Figure 1.1. The equipment is the hardware that enables the animation to be created and observed. The methods are approaches or techniques to realise the animation. The character is the role of the animation which contains two classes: one is the passive-character, who has no motivation and is therefore unable to actively interact with the environment on his own initiative, the other is the active-character, who has motivation and can interact with the environment. There are also special effects cases, where normally passive characters, such as a lamp, are required to become active-characters and perform lifelike animation, such as dancing and jumping. The goal motion is the target motion sequences that the animator wishes to generate. Three types of motion make up the goal-motion: active motion, passive motion and constrained motion. Active motion is generated by the active-character, while passive motion is generated by the passive-character. For example, the motion of a ball falling freely is passive motion while the motion of a person jogging is active-motion. The constrained motion is when an active-character acts on his own initiative, but the result is constrained as for instance, when a man jumps forward. The gesture of jumping can be actively controlled by the character (man). -However, the trajectory

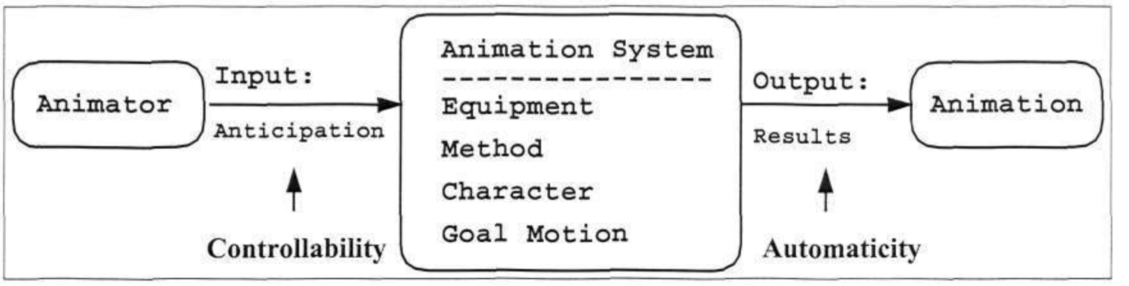


Figure 1.1: Three Essential Factors in computer animation.

of his centre of mass is constrained to a parabola.

An effective animation system possesses two features: (1) it is able to precisely understand the animator's anticipation which is based on the comprehension of a drama, and follow this anticipation interactively to generate appropriate animation. (2) it is able to automatically generate animation with minimal intervention from the animator. In this thesis, the former is referred to as *controllability* to evaluate the input ability of an animation system. The latter is referred to as *automaticity* to judge the capacity of the output of a system. Controllability and automaticity are regarded as two of most important measurements in this study to evaluate an animation system.

If we review the history of animation, we find it is actually a trade-off process between controllability and automaticity. In traditional animation systems, animators mainly used pens and paper as equipment, drew characters directly as the method, and could animate almost all kinds of characters and their motions. Theoretically, since an animator can draw everything and anything he likes, it is evident that the controllability of this system is formidably powerful. The only restriction comes from the imagination and drawing ability. It is possible to achieve a pre-determined anticipation according to a drama, which requires the animation to yield aesthetic as well as harmonious or fluid motion. Although it is currently impossible to accurately quantify and express this aesthetic or harmonious motion using mathematics, and it is also difficult to describe it adequately in words, the human animator can readily solve the problem. Since the human is skilled at perceiving the subtle details the resulting motion is smooth and realistic. But the disadvantage of the traditional system is that the automaticity is extremely defective (poor). It is a time-consuming manual activity.

This disadvantage was so marked, that many researchers kept trying to strengthen automaticity to relieve the workload of the animator. But their efforts met with disappointment because the equipment limited their invention, until, that is, the computer was invented and adopted in the animation equipment. Using the computer, researchers developed a new technique named *kinematic keyframing animation*. The character and the motion are unlimited in this method. To achieve controllability, as in the traditional animation, an animator was able to produce animation by drawing several key frames and interpolating them using the computer, according to his anticipation, just as was done in the traditional animation system. Although the controllability was not obviously improved, the automaticity was significantly improved. However, this was insufficient to satisfy all animators, especially, those who were unfamiliar with the regulation of the locomotion of some characters. Improving the automaticity further was expected by animators.

The expectation that automaticity would improve further was directly related to the improving capability of computers hardware & software. Many researchers are now able to concentrate on new methods which apply the principles of physics to computer animation to develop a physically-based animation system. The major equipment used are more powerful computers. This method is effective when dealing with the motion whose regulation is easily derived from physics, such as a free falling object. Among these particular methods which deal with various types of motion, we are able to observe two major trends which differ by the form of automation. One is *the tailored controller method* which relies on the investigator to hand-tune the controller for animators [71, 48, 23, 35]. Others minimise the animator's intervention and automatically generate animation [67, 9, 22]. Tailored control is also effective for some types of fully-active motion and constrained-active motion. Although in the latter method a variety of motions can be obtained by using different objective functions, and by adjusting the related parameters in the former method. However, it is not easy for an animator to select appropriate objective functions, or to adjust parameters. It is also a formidable task to generate animation according to pre-determined anticipation using these two approaches. This is because many anticipations require the production of aesthetic or harmonious motion based on the drama. So far, it is impossible to judge how aesthetic or harmonious a motion is using an objective function or any other control theory. By applying this animation system, the automaticity is reinforced further. However the controllability is quite poor.

An alternative method of generating motion sequences is by motion capture. This method is heavily dependent on the related equipment. The method involves processing the recorded data which is captured from the actual character and displayed on the screen to generate animation. A character, who is able to coordinate & cooperate with the animator, is suitable for this method. Once the equipment has been adjusted and calibrated precisely, the automaticity is excellent since the motion data is directly recorded from the character, just as in a video tape. However, the motion of the character recorded in the video tape is dressed with fixed surfaces, and the character's motion data captured from motion capture is a set of skeletons, which can be dressed with distinctive clothes or surfaces to portray different characters. For example, this was done in Michael Jackson's performance in "Ghosts". But for those characters who are unable to coordinate with the animator, the controllability is very poor.

Qualitatively, the level of automaticity and controllability is summarised in Table 1.1. In a motion capture system, although both values are relatively high, it is heavily constrained with many appended conditions. With the exception of motion capture, all other methods from traditional systems to physically-based systems, have gradually increased the automaticity, meanwhile, controllability has decreased.

Animation Methods	Controllability	Automaticity
Traditional Animation	High	Low
Keyframe Animation	High	Middle
Physics-Based Animation	Low	High
Motion Capture Animation	High	High

Table 1.1: Automaticity and controllabity features of animation systems. In a motion capture system, although both values are relatively high, it is heavily constrained with many appended conditions. With the exception of motion capture, all other methods from traditional systems to physically-based systems, have gradually increased the automaticity, meanwhile, controllability has decreased.

A question that arises is: is it possible to design a system which is a trade-off between controllability and automaticity? The objective of this thesis is focused on this problem.

1.1 Motivations

Since the physically-based animation control concepts were published, during the last two decades, many kinds of motion styles, for instance, walking, jogging, high jumping etc have been successfully studied in physically-based animation. However, for the special motion style, brachiation, few researchers have involved themselves in the computer graphics, and especially in physically-based computer animation control of brachiation.

Brachiation is a sequence of fascinating movements employed by primates to swing from one tree branch to another by applying appropriate forces. It is certainly extremely difficult to train a real primate to perform the targeted temporal sequences of manoeuvres. However, once a mathematical and computational model for simulating the brachiation of a primate is developed, many desired temporal sequences of brachiation motions of the graphical primate can be generated for computer animation purposes.

Most of the existing research work [60, 57, 58, 59] on brachiation of robots cannot be directly applied to computer animation of brachiation of primate-like creatures. These investigations considered robots with simple models from where it is observed that the motions generated are not natural and realistic.

To control brachiation with high automaticity and high controllability, a physically-based animation control technique needs to be developed. On one hand, this technique should contain a high automaticity technique which may apply artificial intelligent or tailored control techniques to animate brachiation. On the other hand, a novel interactive control should be developed to ensure the high controllability. Further, a completely new and exciting challenge is to develop a methodology which can integrate both control techniques together to include both high automaticity as well as high controllability.

1.2 Objectives

This project considers the development of a novel mathematical and computational framework which possesses high controllability as well as high automaticity for generating realistic motions of the brachiation of primate-like creatures. To achieve the goal of this project, the following objectives have to be accomplished:

- An effective dynamic model for analysing and simulating the brachiating movements must be developed based on the comprehensive research on the brachiation of primate-like creatures. The different complexities of the structural representations of the model must be adequate for depicting the fascinating and realistic motions of the brachiating creatures. The application of this project is not only to generate animation sequences for movie production and advertisements, but also for person-computer interactive control in computer games and simulations where real-time is an essential requirement. Since the requirements for the forementioned two different applications are distinguished, so two different complexity models should be developed to satisfy the application requirements.

- To automatically produce brachiation motion, a high automaticity control framework which adopts a tailored control method must be devised to facilitate the process of animating the brachiating creatures.
- To further improve automaticity, a self-adaptive learning framework needs to be proposed and implemented for exploiting the experiences gained from the exploratory phases of the primate-like creatures.
- To improve controllability, a physically-based interactive module must be developed for controlling the trajectories and locomotion of the brachiating primate-like creatures. The interactive module should provide mechanisms for the user to describe and plan the trajectories of the brachiating creatures in a real-time manner.
- Modules to integrate the high automaticity modules with the high controllability module to further improving and synthesising both controllability and automaticity into an integrative control must be developed. These modules should be more convenient for the animators who are experts or amateurs at generating brachiation motion sequences.
- Extensive experimental results must be reported to demonstrate the effectiveness and robustness of the mathematical and computational frameworks for physically-based aniamtion and simulation, controller design and learning plau-

sible controllers. Realistic animation sequences must be generated to illustrate the automaticity and controllability features of the proposed brachiation animation system.

1.3 Organisation

The organisation of the thesis is described as follows. A literature survey on computer animation of articulated bodies is presented in chapter 2. In particular, the details of the existing research work on computer animation, robotic simulation and biomechanics of brachiation are described. The strengths and weaknesses of the reported research work are discussed.

Chapter 3, describes the dynamics formulation and control mechanisms for producing realistic swinging and grasping motions of a simplified primate-like model. The functionality and behaviours of the essential controlled parameters are discussed.

Chapter 4 presents the tailored control framework of the proposed animation approaches for generating brachiating movement of primate-like creatures.

Chapter 5 presents the heuristic control framework of the proposed animation approaches for heuristically and automatically generating brachiating movement of primate-like creatures.

Chapter 6 presents the interactive control method interactively generating brachiating movement of primate-like creatures according the requirements of the animator.

Chapter 7 presents the integrative control method for synthesising tailored, heuristic and interactive control to improve both controllability and automaticity.

In Chapter 8, experimental results are reported to verify the computational effectiveness and realism of the brachiating motions of a primate-like creatures when subjected to a few typical working conditions.

Finally, conclusions are drawn in Chapter 9. The problems which have arisen from the current proposed animation framework are analysed and their potential solutions are discussed in the future work.

Chapter 2

Survey of Computer Animation Relevant to Brachiation

In this chapter, a literature survey on computer animation is presented. In particular, a detailed discussion is devoted to the areas of computer animation, robotics and biomechanics for brachiation.

First, the roles of kinematics and dynamics for computer animation are explained and the existing works based on these approaches are summarised. Next, recent approaches employed in solving the problems in computer animation are briefly described. Finally, promising work in the areas of computer animation, robotics and biomechanics related to brachiation of primate-like characters is discussed in details.

2.1 Kinematics-Based Approaches

Many of the commercial animation systems for generating animation sequences are based on kinematic approaches. Kinematics-based modules of these animation systems generally provide intuitive control mechanisms but are lacking in physical integrity. Kinematics approaches may be divided into forward and inverse kinematics. Methods based on forward kinematics involve the designation of keyframes by specifying the angles of each joint of the articulated figures. In the case of inverse kinematics, the end effector of the chain of a simulated character is specified by the user and the required joint angles to achieve the goal are automatically determined. Animated figures created using these approaches do not seem to possess basic physical components such as gravity or inertia. Generally, joint limits and goal-oriented constraints are incorporated into the inverse-kinematics framework for facilitating the process of generating realistic postures.

The inverse kinematics-based approaches [50, 6, 21, 32] have been successfully applied to the generation of many fascinating and complex postures of creatures by skillful and experienced animators. Kondo [31, 30] developed a kinematics-based method for producing desired human arm postures and generating realistic sequences of motions of human arms. The algorithm is based on the neurophysiological behaviour of the human arm posture and is mainly determined by a sensorimotor transformation model. This model describes the linear mapping relation between the parameters of the arm posture and spherical coordinates centered on the shoulder. Representative examples such as manipulating eyeglasses and cooperative manipulation of a chess box were demonstrated using their animation system.

The strengthes and weaknesses of kinematics-based animation systems can be described as follows:

Strengths

- Kinematics-based approaches provide an animator with full control over the postures, constraints and movements of articulated characters. The mechanisms for manipulating three-dimensional articulated bodies are intuitive.
- Generally, the computational load for solving the kinematics problems is relatively low. Hence, the manipulation of the objects can be achieved at an interactive speed.

Weaknesses

- A vast amount of training and experience is required in specifying the positions of the relevant joints for producing realistic and fascinating movements of animals with complicated structures. This is mainly because the highly interdependent links of an articulated figure will exponentially increase the complexity and load of the manipulation tasks with respect to the degrees of freedom of the figure.
- Animated characters produced using this method are not able to realistically interact with a dynamic and unpredictable environment.

2.2 Dynamics-Based Approaches

Dynamics-based simulation for computer animation involves the generation of realistic motion sequences of characters by simulating their physical behaviour under the influence of the physical laws of motion. Just like the kinematics approaches as introduced in the previous section, dynamics-based approaches may be divided into two categories; namely: forward and inverse dynamics. Methods based on forward dynamics involve the computation of the motion of an object by applying appropriate time-varying forces and torques to the object. Inverse dynamics-based methods determine the required forces and torques to be applied to an object in order to obtain a desired motion trajectory. Both simulation techniques take into account the physical characteristics of an object, such as mass, inertia, gravity and collisions.

Armstrong [3] and Wilhelms [66] were pioneers in using dynamic simulation for computer animation of the human body with moderate complexity. Railbert [47] developed a well-known one-legged robot based on forward dynamics simulation and a state-space machine approach. The results were extended to generating running and hopping sequences of a biped robot, a quadruped robot and a simplified kangaroo model [48].

Beside considering dynamic simulation of legged bodies, dynamic simulation of creatures based on contraction and expansion of muscles were also considered. In this aspect, Miller [37] developed a simplified snake model for generating sequences of snake progression gaits. The evaluation of the values of the muscle actuators was very complicated and non-traceable. Furthermore, the animator needed to input appropriate values for many control variables for performing other gaits and movements of snakes. These values had to be gleaned by studying and modifying the biological data and knowledge of snakes and worms from the experimental biology literature. This is a non-trivial task.

McKenna et al. [36] developed a method based on forward dynamics and biological mechanisms for generating realistic locomotion of six-legged creatures. The dynamics simulation algorithm used in the system for computing the movements of a six-legged simulated insect was based on Featherstone's work [15, 16]. Featherstone's dynamics simulation was employed in their work because the algorithm is accurate, general and computationally efficient. A gait controller based on a coupled oscillator model with reflexive feedback components was employed for coordinating the gait sequences of stepping and stance phases of the six-legged insect. The oscillator model derived from biological observations was based on the work of Wilson [65] and Pearson et al. [42].

Tu et al. [63] developed a dynamic fish model based on Miller's work for simulating fish swimming. The authors also considered and significantly extended the methods by incorporating flocking and behavioural models into their animation framework. Similarly, the controlled parameters of the simulation of the fish swimming motions were determined by a laborious hand-crafting process.

The advantages and disadvantages of the existing animation frameworks based on dynamics are as follows:

Advantages

- The motion sequences generated using dynamic approaches generally look natural and realistic because the objects are simulated under the influence of physical forces. This can be achieved with minimal intervention.
- The realistic motion of an object is determined by its reactions and interactions with a simulated physical environment.
- An effective physical model of a creature or an object can be applied to model a wide range of possible movements.

Disadvantages

- To simulate a character with moderate complexity, dynamic-based approaches require extensive computational load to solve the dynamic equations of motion. Hence, this time-consuming process is unable to allow real-time interactions with the simulated object.
- Generally, it is a challenging task to propose appropriate forces and torques for controlling and generating realistic motion of objects. Many hypothesised candidates have to be explored and fine tuned before natural and smooth trajectories can be achieved.

2.3 Recent Approaches for Computer Animation

Recently, many interesting animation systems based on various different approaches and paradigms have been proposed and developed for facilitating the process of generating realistic animation sequences of articulated figures. For instance, Arikan and Forsyth [2] presented a framework that generates human motions by cutting and pasting motion capture data. Furthermore dynamics-based methods have been integrated into some hybrid frameworks for producing relatively complicated motion sequences.

Spencer [56] used genetic programming to automatically create programs that enable a simulated six-legged insect to walk and to accomplish this automatic action with a minimum of assumptions about how walking should occur. He demonstrated that genetic programming generates successful and efficient programs capable of making an artificial insect walk in a simulated environment. This approach required very little specific domain knowledge. However, Spencer's system was unable to handle dynamics and unpredictable situations.

An interesting approach; namely, controller synthesis, was proposed by Van de Panne et al. [43] for generating realistic movements of articulated figures by evaluating appropriate control inputs to actuators of the joint angles. The desired motion of the figure was provided and the corresponding motion controller was optimised based on a performance measure. In their work, a dynamic programming approach was used to determine a set of optimal parameters for a motion controller. Later, Van de Panne et al. [44] extended the controller synthesis approach to search for feasible solutions depicting disparate motion characteristics from a global region of the state space. In this work, the motion controller was referred to as a sensor-actuator network of which the dynamic behaviour was affected by the connection weights and timing constants. The potential solutions associated with meaningful motion characteristics were evaluated in two stages. The first stage was a random generate-and-test procedure for identifying coarse solution regions. In the second stage, simulated annealing was employed to refine the coarse solutions by establishing the best controllers. Unlike local optimisation approaches, the selected controllers can be situated far apart from each other in the search space. If the target motion of creatures is periodic, a cyclic pose control graph can be employed to represent the initial search space of the periodic motion controllers [45]. The nodes and arcs of the graph represent the pose configuration and transition times set between the nodes, respectively. Having established the cyclic pose control graph, a fine tuning process can be used to determine feasible solutions efficiently. However, the design of an appropriate pose control graph requires extensive experiences and hand-crafting experiments.

Ngo and Marks [38] proposed an automatic synthesis of motion controllers similar to the sensor-actuator network approach by Van de Panne et al. [44]. The feasible solution regions were searched using a heuristic approach based on a genetic algorithm. In their work, an initial population of chromosomes (i.e. motion controllers) were generated by sampling the search space. Next, mutation and crossover operators were applied to the population of chromosomes to generate good solutions associated to stimulus and response parameters of the plausible motion controllers. The fitness functions of the candidates were designed using the evaluation criterion for the desired motion behaviour. It is a non-intuitive and difficult task for animators to input the fitness functions associated with their desired motion characteristics. The published research experimented with simple two-dimensional figures. It is envisaged that the extension of the paradigms to three-dimensional figures with moderate degrees of freedom would be computationally heavy.

2.4 Brachiation

In this section, a survey of brachiation and closely related problems in the areas of computer animation, robotics and biomechanics is presented.

Spong [58, 59] studied extensively the swing up problem of a two link robot, called acrobot. To solve the swing up problem, the author proposed two different algorithms based on the concept of partial feedback linearization for establishing a linear response from each degree of freedom of the joints (i.e. shoulders). The details of the linearization technique can be found in Isidori [24]. The first algorithm was developed to deal with cases where no limitation was imposed on the angle of rotation of the free link. In the case of free link with restricted angle of rotation, the second algorithm was applied to accomplish the goal. Experimentally, the author demonstrated the feasibility of the proposed algorithms for solving the swing up problem. However, it appears that Spong's method can be employed to solve only a small portion of the brachiation problem. Furthermore, the response of the system is very sensitive to certain control parameters which requires extensive trial and error processing before an appropriate set of parameters can be found. To solve this tuning problem, DeJong and Spong [12] developed a control strategy for learning and generalising the dynamic model of a two links acrobot. The proposed control strategy was based on an explanation-based learning which was derived automatically from a symbolic artificial intelligence model [11]. The symbolic world model consisted of processes and inference rules. The processes describe the behaviour of the acrobot while the inference rules encode information to the inference system about the general relationships between quantities and their changes. The process and inference rules were chained together to form axioms for explaining the observed dynamic behaviour of an example of the swing up motion of an acrobot. After constructing the symbolic explanation using the derived axioms for a desired goal, the system can automatically optimise the required motion characteristics of the acrobot. The construction of a symbolic qualitative model for representing the dynamic characteristics of an acrobot is a difficult task. This becomes worse if the complexity of the structure and motion characteristics of the acrobot increase. The search space of such a symbolic model can be very large.

Takashima [60] developed a method to control a gymnast robot for generating some fascinating motions on a high bar. The gymnast model contained three links. The swing-up motion was achieved by two mechanisms: one changed the position of the center of mass of the model according to the results of sensing which used the conditions of angular momentum of the model; the other manipulated the frequency of the sinusoidal joint angle movement as a function of the angular amplitude of a swing. To accomplish a handstand state on a high bar, a look-up table was first generated off-line. This table was constructed by measuring the loss of kinetic energy during one rotation of a giant swing caused by a specific swing-suppressing movement of the joint angles. This simulation was repeated for various initial conditions of the kinetic energy of the figure. During a run-time simulation, the initial kinetic energy was first computed from the joint angular velocities of the links of the gymnast model and the value was then used to identify an appropriate table. An appropriate joint angle was selected to reduce the kinetic energy to an allowable tolerance threshold (i.e. nearly zero). It is anticipated that the complexity and dimensionality of the representation of the look-up table will increase exponentially if the degrees of freedom of the gymnast model increase. Nevertheless, the concept of applying a learning mechanism for estimating feasible desired states to accomplish target motion characteristics is worth consideration in future work. Takashima's work is only able to solve part of the brachiation problem.

Saito et al. [52, 53] proposed a heuristic algorithm to generate a feasible sequence of driving input signals for the motor driver of the joint of a two-link robot without any a priori information on the dynamics of the robot. These driving inputs were employed to produce a sequence of brachiating movements. These appropriate driving inputs were searched for by minimising an evaluation function. The evaluation function was designed to measure the energy dissipation of a moving robot and the distance between the robot's grip and the target bar. The velocity of the grip was also monitored for facilitating the catching of the bar without causing excessive impact on the bar. Having generated a coarse motion trajectory of brachiation, a trajectory feedback control was employed to maintain a minimum difference between the actual and ideal trajectories. Once, the grip reached the feasible region, arm-direction feedback control was applied to the robot grip to grasp the target bar precisely and realistically. Extensive experimental results were reported to verify the performance of the proposed control framework. The author realized that the proposed heuristic method for computing appropriate input signals had by no means retained or reused the available historical information produced during the trial process of the learning phase. Later, Saito [54] applied a Q-learning technique for learning the useful and new sequences of experiences encountered during the trial process of the heuristic method. A connectionist network was employed to represent these learned experiences. By doing so, the learned experiences could be generalised to deal with new states and the input-output mapping function could be represented by a continuous space. The experience sequences memorised in the network were employed to design utility functions mapping each state to the optimal actions for accomplishing the desired motion characteristics.

Chang et al. [8] described a transducer system and analysis strategy that allows the dynamic force and moments applied by brachiator to be determined. Preuschoft and Demes [46] conducted a rigorous study on the biomechanics of brachiation of apes. The authors clearly explained and illustrated the biomechanical advantages exhibited by elongated forelimbs of apes in the forms of arboreal locomotion (i.e. brachiation). Fleagle [17, 18] and many other researchers [46] performed an analysis and comparison between gibbon brachiation and the dynamics motion of a pendulum. It is said that the mathematical model of a pendulum corresponds reasonably well for gibbons brachiating at moderate speed and is well suited for simulating brachiating animals with long forelimbs.

Usherwood et al. [64] developed two point-mass models for two different brachiations: continuous-contact brachiation and ricochetal brachiation. Nishimura and Funaki [39] presented a brachiation motion control based on a 3-Link model which applied final-state control for a linear parameter-varying system with error learning. The three links of their 3-Link model connected one-by-one serially. Distinctly, Timm and Lipson [62] developed a parallel connecting three links model where two arm links connect the shoulder of the third torso link. They developed a genome algorithm which contained the initial position at the starting time and a torque function applied to the shoulder. The brachiation motions were measured by total distance travelled and energy-efficiency of locomotion.

Fukuda et al. [20, 26, 27] considered "Brachiation" as one of the most dynamic motions in animal motions. They introduced a multi locomotion robot which could select the appropriate locomotion from biped locomotion, quadruped locomotion and brachiation according to the required environment. The controller contained a hierarchical behaviour-based control and an enhanced learning control.

Different from those works, we focus on the integrating technique for improving controllability and automaticity simultaneously within physically-based animation control. The author's early work on interactive control [72] [73] proved that interactive control is appropriate for a 3-Link Hylobate model and integrative control is efficiency for improving both controllability and automaticity. One year later, Laszlo et al [33] published a similar idea to interactively control the torques of models through a mouse input. The idea of synthesising controllability and automaticity, i.e. control that integrates low-level interactive control with middle-level tailored control and high-level heuristic control, was first presented by the author [72] [73] in computer animation.

Having studied the biomechanical aspect of Hylobates in brachiation, this knowledge can be employed for proposing a generic Hylobate model and for proposing an effective mathematical and computational framework to simulate realistic brachiating motions.

2.5 Summary

In this chapter, a survey on kinematics-based, dynamics-based methods as well as more recent methods for computer animation are summarised. Unlike other locomotion simulations, there are very few research results available on the brachiation of primate-like creatures. A detailed discussion of the various methods of simulation of brachiation and their related motions has been given. In summary, the drawbacks and potential problems of these existing systems for generating brachiating motions are as follows:

- Most structures of existing primate-like models, such as point-mass, 2-Link and 3-Link models, are too simple (except for the model developed in Fukuda's Lab.); hence these models are inadequate for expressing the realism of brachiation.
- The problem of how to generate realistic and natural motion for the purpose of animation has not been researched.
- A method synthesising the different control levels in order to improve automaticity and controllability has not yet been proposed.

The above mentioned problems are carefully considered in the following chapters.

Chapter 3

Brachiation: Model and Equation

The process of designing a physically-based animation system consists of four steps: analysing a target motion, determining a character model, deriving dynamic equations and designing the motion controller. First, the analysis of target motion should describe the motion sequences and features clearly according to the requirements of an animator. In the second step, determining a character model corresponds to designing a model of proper complexity to achieve the target motion according to the purpose of the animation, in realtime or non-realtime. In the third step, deriving dynamics equations corresponds to deriving functions which can calculate convincing kinematics data, such as position, velocity and acceleration from torques or forces. In the fourth step, designing a motion controller which provides appropriate forces or torques to generate satisfying motion is developed. The first three steps are introduced in this chapter, the fourth step, the core of this thesis, is presented in subsequent chapters.

3.1 Target Motion: Brachiation

Brachiation (see an example in Figure 3.1) is a very special motion style that possesses three features: (1) It is an under-actuated system which means that the number of actuated degrees of freedom (actuated DOFs) is one less than the systems total number of DOFs. This indicates that there is at least one non-directly controllable DOF or joint, called a passive DOF or passive joint. (2) During brachiation, the hylobate who is performing the brachiation would keep holding a bar, called the hold, with the palm of its right hand during brachiation. The DOF connecting the palm with the hold is a unique passive DOF that connects the brachiator with the outside environment while it is brachiating. (3) It is very difficult to achieve a required gesture when compared with other stable systems. For instance, if we need to animate an arm throwing a ball the first shoulder joint must be controllable. The major task of brachiation is swinging and grasping a target. During the swinging and grasping motion, it is very hard to control the gesture of a brachiator. Even a small action, for instance cringing (bending) the free-swinging arm, may disturb the swinging and grasping motion and cause the brachiation to fail. These features require detailed analysis of the brachiation process.

In nature, there are many kinds of species of primate that can perform a variety of brachiations. The most famous experts are Hylobates which contains two categories: siamangs and gibbons. This indicates that different species may brachiate in different ways; the same species of different sex could brachiate in different ways; even if they are of the same sex, an old brachiator could brachiate differently from a younger one. The same brachiator, under different environmental or emotional conditions may produce various motions, for instance the motion of the links generated under happiness is evidently different from the motion under sadness or fear. The brachiation generated when the brachiator is intending to pick a fresh fruit is different from that when he is trying to escape from a dangerous predator.

From the viewpoint of gesture, a brachiator may curve its lower limbs or extend them. Due to such a wide variety of brachiation motions, we cannot design a controller to appropriately produce all forms and variations of brachiations without any modification. It is unnecessary and impossible to fulfill such a complex task in a single Ph.D thesis. This thesis is concerned with the features of a generic style of brachiation.

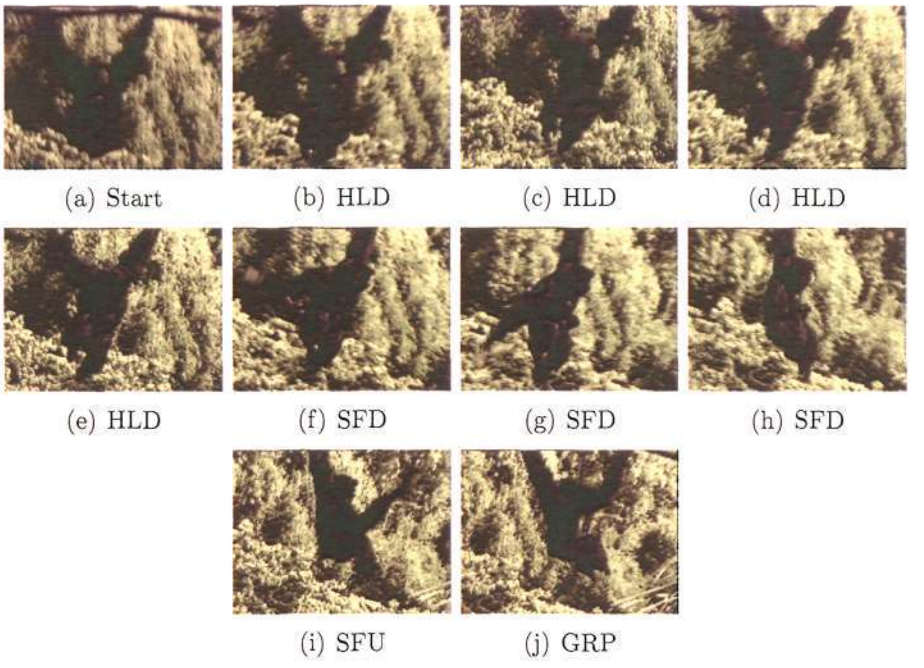


Figure 3.1: The brachiation of a Hylobate downloaded from the Oakland Zoo website [40].

However, applying control should allow us to generate other brachiations. Below, the details of the brachiation motions targeted in this thesis are presented.

To determine the features of brachiaton, a variety of methods have been investigated. These include, going to the zoo and observing living lesser ape's brachiations, reading related books that describe motion patterns of brachiation, and researching movies of brachiation on the internet. Based on these observations an overall approach to modelling brachiation is proposed.

At the beginning (as shown in Figure 3.1 (a)) of a brachiation motion sequence of a Hylobate (downloaded from the Oakland Zoo website [40]) the brachiator is holding the bars with both the right and the left hands. In the following figures (Figure 3.1 (b) to (e)), an interesting phenomenon can be observed: the brachiator is pulling its Center of Gravity up by adjusting its body while holding the bars with both its left and right hands. To the best of our knowledge this motion sequence, called the Holding (HLD) phase, has not yet been studied and animated in the scope of brachiation research. The amazing features of the HLD phase will be detailed in the following section.

After that, the brachiator releases the right hand and swings down and forward; we call this phase a Swing-Forward-Down (SFD) phase, as shown in Figure 3.1 (f), (g) and (h). After passing the middle and lowest level of swing, the brachiator starts swinging forward and up (Swing-Forward-Up (SFU) phase), as shown in Figure 3.1 (i). After SFU, if the swing is not strong enough for the brachiator to grasp the target, it would swing backward and down (Swing-Backward-Down (SBD) phase), and swing backward and up, (Swing-Backward-Up (SBU) phase) and swing forward again (SFD+SFU). Otherwise, the brachiator will grasp the target (Grasp (GRP) phase), as shown in Figure 3.1 (j). When the distance between the target and the grasping hand is less than a certain value, it is assumed that the brachiator has successfully grasped the target.

We may conclude that the entire brachiation sequence contains six phases: HLD, SFD, SFU, SBD, SBU, and GRP, as shown in Figure 3.2. It is often observed that hylobates are able to swing forward just once and grasp the target successfully. The process reduces then to HLD, SFD, SFU, and GRP, as shown in Figure 3.1 (a) to (j); we call this process Swing-Forward-Once-Grasp (SFOG). SFOG brachiation is a more challenging task for our animation control system because from the phase HLD to GRP it has only one chance to successfully grasp the bar. It requires more efficient control during the SFD phase so that in the GRP phase the brachiator has adequate energy to grasp the target.

In this section, we have described each swing phase in qualitative terms. One of the purposes of this thesis is to analyse and model quantitatively all these phases. An analysis of each phase from the viewpoint of energy and motion posture is presented below. This is used later in the model proposed in section 3.2.

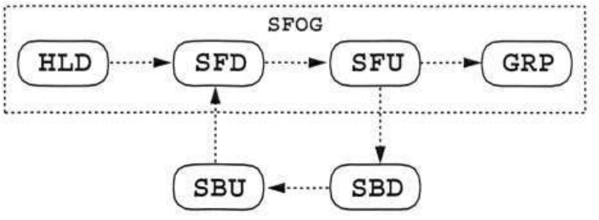


Figure 3.2: Swing phase of Brachiation. SFOG contains the first line phases: HLD, SFD, SFU and GRP

3.1.1 Features of Swing-Forward-Down (SFD)

According to the laws of physics, at the beginning of the SFD phase, the total energy is $E_b = E_{Pb} + E_{Kb}$, where, E_{Pb} is the potential energy and equals $m * g * h_b$, where m is the mass of the system; g is the gravitational acceleration of the earth; and h_b is the vertical distance from the Centre of Mass (COM) to the bar. In this thesis, it is assumed that the position of the holding bar is the zero potential energy. E_{Kb}, the kinetic energy, is zero at the beginning, since there is no movement at the beginning.

At the end of the SFD phase, the total energy is equal to the potential energy $E_{Pe} = m * g * h_e$, where h_e is the vertical distance from the Centre of Mass (COM) to the hold bar, plus the kinetic energy, E_{Ke}, $E_e = E_{Pe} + E_{Ke}$. Because we assume that the total energy is conserved, $E_b = E_e$, the kinetic energy at the end of the SFD phase is equal to the difference between the beginning and ending potential energies. $E_{Ke} = E_{Pb} - E_{Pe} = m * g * (h_b - h_e)$.

There are at least two feasible ways to gain more kinetic energy at the lowest level of swing: one way is to increase h_b at the beginning of brachiation; the other way is to extend the body to let the value of $h_b - h_e$ be greater. This could be achieved by extending the grasping arm or lower limbs at the lowest level of the SFD phase. This can be observed in Figure 3.1 (f), (g) and (h), and Figure 3.3 (b).

3.1.2 Features of Swing-Forward-Up (SFU)

From the viewpoint of energy, when the brachiator is in the SFU phase, it will try to convert more kinetic energy to potential energy. There are different ways this can happen. The first one is swinging the grasping arm up towards the right side; it will pull the COM up. The second one is curling the lower limbs up; this will also improve the potential energy. After observing many brachiations of actual hylobates, it was noted that the trunks of brachiators are usually almost perpendicular to the ground during SFU, as shown in Figure 3.1 (i) and Figure 3.3 (c).

3.1.3 Features of Swing-Backward-Down (SBD)

From the point of view of energy, in a similar manner to the SFD phase, the brachiator will try to convert more potential energy to kinetic energy. This can be achieved by reaching the lowest potential energy at the lowest level of this phase by extending the grasping arm and lower limbs, as illustrated in Figure 3.3 (f).

3.1.4 Features of Swing-Backward-Up (SBU)

This phase is similar to the SFU phase. The brachiator will try to convert more kinetic energy to potential energy. The brachiator swings the grasping arm (see Figure 3.3 (e)) backward and up, and curls the lower limbs to realise this target.

3.1.5 Features of Grasp (GRP)

In this phase, the aim is to grasp the target with an appropriate posture. Through observation of real brachiations of Hylobates, it is concluded that the brachiator's trunk is almost perpendicular to the ground at this moment, and the lower limbs are curled. This may be useful to continue to the next brachiation with fluid motion, as shown in Figure 3.1 (j) and Figure 3.3 (d).

Name	Implication
RLA	Right Lower Arm
RUA	Right Upper Arm
TRK	Trunk
LUA	Left Upper Arm
LLA	Left Lower Arm
RUL	Right Upper Leg
RLL	Right Lower Leg
LUL	Left Upper Leg
LLL	Left Lower Leg

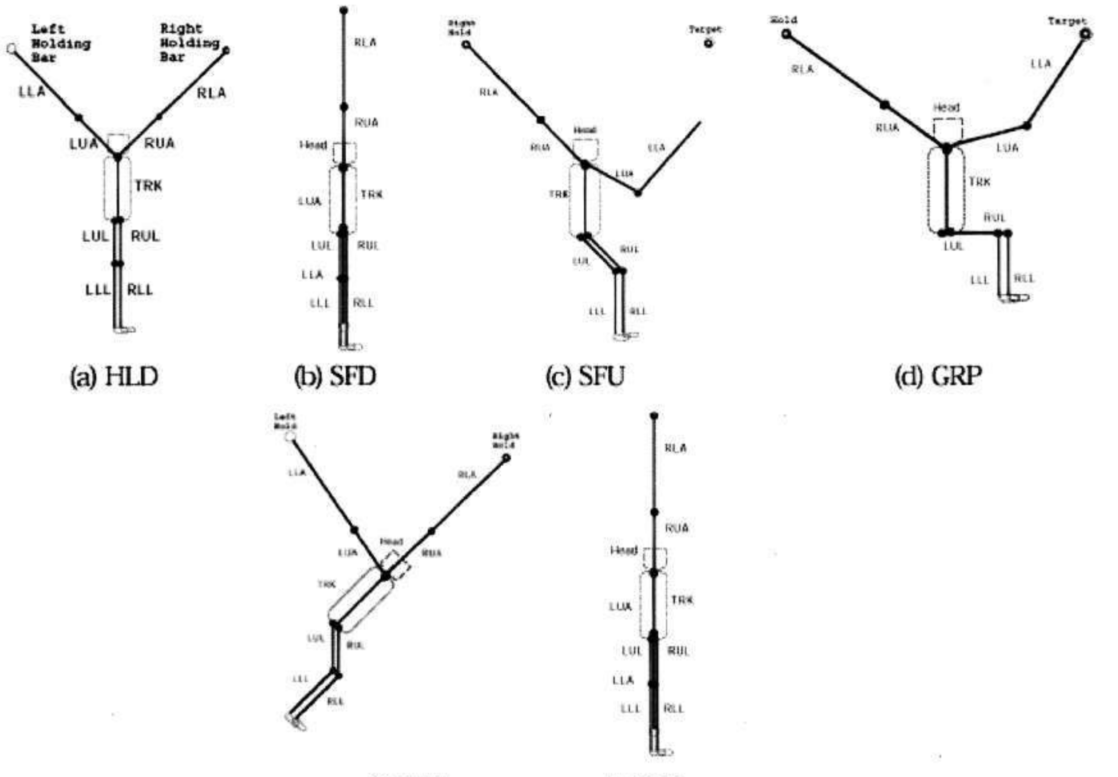


Figure 3.3: The desired ending poses of each of the six brachiation phases. The upper row from left to right illustrates the key gestures of the four phases of SFOG: HLD, SFD, SFU and GRP. They are related to Figure 3.1 (b), (h), (i) and (j) respectively. The bottom row shows the key postures of SBU(left) and SBD(right).

3.2 Character Model

The more complex the structural model is, the more realistic the motion will be. But the related computing cost is heavy and the controller is difficult to design. Hence an appropriately complex model should be determined.

In their prior work, many authors [19, 57, 58, 53, 52] have modelled characters with two links that only represented left arm and right arm. Others [60] constructed the character with three links with the three links connected in series like a chain. These studies could not simulate the motion of the swinging arm, trunk and the lower limbs of the brachiator simultaneously. As we want to simulate these movements, a more sophisticated approach must be taken.

In this thesis, one of the main objectives is to explore a method for enhancing controllability and automaticity in the brachiation system. The controllability and automaticity of a simple model are apparently simpler than those of a complex one. How does the complexity of a model affect the final control? This is studied in this work. Two models were constructed with different complexities, one was a simple 3-Link model, the other was a more complex 9-Link model. They point to different directions: the simple model tries to simplify the problem to test the feasibility of the control ideas and apply it in real-time application (such as on-line games), the more complex model is oriented towards producing more sophisticated brachiation motion sequences for movie production and need not necessarily be produced in real-time.

The two different models, 3-Link model and 9-Link model, are composed of the following components: links, joints and sensors. Links and joints are easily understood, while sensors are a little complex. The job of sensors is to determine the type of motion. There are three kinds of sensors used in this thesis: angular sensors, collision sensors and orientation sensors. An angular sensor measures the position of one link, a collision sensor determines the distance between two specific points, and an

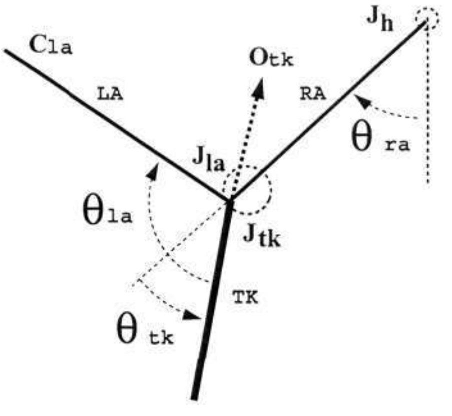


Figure 3.4: 3-Link model: links, joints and sensors.

orientation sensor estimates the orientation of one link. Since brachiation is considered in the 2-dimensional space in this thesis, so orientation sensors are specified by angles with respect to certain lines as references. The details of these components are presented in the following sections for the two different models.

3.2.1 3-Link Model

Links

In the 3-Link model, we mimic the brachiator using 3-Links connected in a natural looking style, as shown in Figure 3.4. A right arm link, RA, and a left arm link, LA, are connected to the trunk link, TK, as indicated in Table.3.1. To simplify the problem, all 3-Links are assumed to be uniform solid cylinders.

Link	Name	Implication
L0	RA	Right Arm
L1	TK	Trunk
L2	LA	Left Arm

Table 3.1: 3-Link model: Links.

Joints

The 3-Links are connected by non-friction rotary joints. There are two kinds of joints in the 3-Link model: actuator joints and passive joints. As shown in Figure 3.4, the joint, J_h, between the hold and the right arm link cannot be directly controlled by the brachiator's torque and the resistance is neglected, so we assign it as a passive joint. The others, J_{tr} and J_{tl}, are actuator joints where we can apply active torques to pump energy into the system to grasp the target bar. The joints are listed in Table 3.2. Because the total number of joints is three, and the number of actuator joints is two, the system is referred to as an underactuated system.

Joint	Name	Feature	Connection between
J0	J_h	Passive Joint	Right Arm and Holding Bar
J1	J_{tr}	Actuator Joint	Trunk and Right Arm
J2	J_{tl}	Actuator Joint	Trunk and Left Arm

Table 3.2: 3-Link model: Joints.

Sensors

In the 3-Link model, as shown in Figure 3.4, there are three angular sensors, θ_{ra}, which measures the angle between the right arm link, RA, and the vertical axis, θ_{tk}, measuring the angle between the trunk link, TK, and the right arm link, and θ_{la}, measuring the angle between the trunk link and the left arm link, LA. There is only one collision sensor, C_{la}, and one orientation sensor, O_{tk} in the three link model. C_{la} measures the distance between the palm of the left arm and the target and indicates how close the brachiator is from catching the target. Since the brachiation is considered as a 2D motion in this thesis, the O_{tk} can be applied to measure the orientation of the trunk with respect to the vertical axis and determine the posture of the brachiation. All the sensors are listed in Table 3.3.

Angular Sensor	Name	Implication
A_0	θ_{ra}	Angle between L0 and vertical axis
A_1	θ_{tk}	Angle between L1 and L0
A_2	θ_{la}	Angle between L2 and L1
Collision Sensor		
C_0	C_{la}	Collision detection between grasping palm and target
Orientation Sensor		
O_0	O_{tk}	Measuring the orientation of Trunk

Table 3.3: 3-Link model: Sensors.

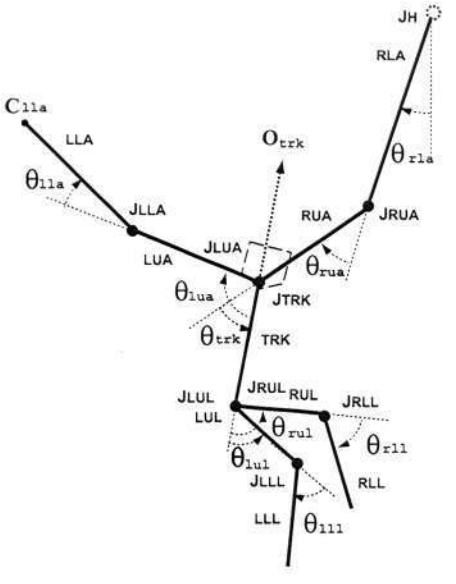


Figure 3.5: 9-Link model: links, joints and sensors.

3.2.2 9-Link Model

Links

In the 9-Link model, the brachiator is modelled using 9 Links as shown in Figure 3.5, namely the right lower arm (RLA), the right upper arm (RUA), the trunk (TRK), the left upper arm (LUA), the left lower arm (LLA), the right upper leg (RUL), the right lower leg (RLL), the left upper leg (LUL) and the left lower leg (LLL). They are also listed in Table 3.4. As the motion of the brachiator's head and the feet are not evident compared with the other links (for example the limbs), the head and the feet are neglected in the model. Animating the motion of grasping fingers is another major research issue in computer animation which is quite different from our brachiation motion control, so the palms and fingers are also ignored in the 9-Link model.

It is a major challenge to obtain biomechanical data of a real animal. In this thesis, the biomechanical data of the 9-Links are derived from Yamazaki's work [70]. This data is evaluated using the method presented by Jensen [25]. They calculated the size and mass distributions of the modelled segments using geometrical calculations.

A body segment is divided into many elliptical plates. Both major and minor axes of each plate are measured from frontal and lateral photographs.

Link	Name	Implication
L0	RLA	Right Lower Arm
L1	RUA	Right Upper Arm
L2	TRK	Trunk
L3	LUA	Left Upper Arm
L4	LLA	Left Lower Arm
L5	RUL	Right Upper Leg
L6	RLL	Right Lower Leg
L7	LUL	Left Upper Leg
L8	LLL	Left Lower Leg

Table 3.4: 9-Link model:Links.

Joints

Similar to the 3-Link model, we consider the joints connecting these 9-Links as non-friction rotary joints. As shown in Figure 3.5, except for the joint connecting the holding bar and the right lower arm (J_H), which is a passive joint, all others, J_{RUA}, J_{TRK}, J_{LUA}, J_{LLA}, J_{RUL}, J_{RLL}, J_{LUL}, and J_{LLL} are actuator joints. As listed in Table 3.5, the total number of joints is nine, meanwhile the number of actuator joints is eight, so the system remains an underactuated system.

Joint	Name	Feature	Connection between
J_0	J_H	Passive Joint	RLA and Holding Bar
J_1	J_{RUA}	Actuator Joint	RUA and RLA
J_2	J_{TRK}	Actuator Joint	TRK and RUA
J_3	J_{LUA}	Actuator Joint	LUA and TRK
J_4	J_{LLA}	Actuator Joint	LLA and LUA
J_5	J_{RUL}	Actuator Joint	RUL and TRK
J_6	J_{RLL}	Actuator Joint	RLL and RUL
J_7	J_{LUL}	Actuator Joint	LUL and TRK
J_8	J_{LLL}	Actuator Joint	LLL and LUL

Table 3.5: 9-Link model: Joints.

Sensors

There are three kinds of sensors in the 9-Link model, angular sensors, collision sensors and orientation sensors, as shown in Figure 3.5. The implications of the angular sensors are described in Table 3.6. The only collision sensor, C_{lla}, measures the distance between the palm of the left hand and the target; it indicates how close the brachiator is from grasping the target. The orientation sensor, O_{trk}, which measures the orientation of the trunk with respect to the vertical axis, represents the posture of the brachiator. All the sensors are listed in Table 3.6.

Angular Sensor	Name	Implication
A_0	θ_{rla}	Angle between RLA and vertical axis
A_1	θ_{rua}	Angle between RUA and RLA
A_2	θ_{trk}	Angle between TRK and RUA
A_3	θ_{lua}	Angle between LUA and TRK
A_4	θ_{lla}	Angle between LLA and LUA
A_5	θ_{rul}	Angle between RLL and TRK
A_6	θ_{rll}	Angle between RLL and RUL
A_7	θ_{lul}	Angle between LUL and TRK
A_8	θ_{lll}	Angle between LLL and LUL
Collision Sensor		
C_0	C_{lla}	Collision detection between grasping palm and target
Orientation Sensor		
O_0	O_{trk}	Orientation of Trunk

Table 3.6: 9-Link model: Sensors.

3.3 Dynamics Equation

Generally, as described by Craig [10], there are two different problems related to the dynamics equation involving the forward dynamics system and the inverse dynamics system. In the inverse dynamics system, a set of trajectory points, the vector of joint angles (Θ), velocities ($\dot{\Theta}$) and accelerations ($\ddot{\Theta}$) are provided, and the proper vector of joint torques τ have to be computed. It is useful for controlling a robot to perform some required motion. However it is not suitable for the requirements of this thesis, because it is tremendously difficult to obtain the exact natural looking trajectories of each link of the brachiator; otherwise, we could just draw the links according to the obtained trajectories and there would be no need to compute the torques or forces. Alternatively, the forward dynamics system calculates how the links will move, and outputs $\Theta, \dot{\Theta}, \ddot{\Theta}$, under the application of a set of given joint torques, τ. It is useful for both animation and simulation. The relevant equation is:

$$\ddot{\theta} = M^{-1}(\theta)[\tau - V(\theta, \dot{\theta}) - G(\theta)] \tag{3.1}$$

where, M^{-1} is the inverse inertial matrix, $V(\theta, \dot{\theta})$ is an $n * 1$ vector of centrifugal and Coriolis terms, and $G(\theta)$ is an $n * 1$ vector of gravity terms.

Given initial conditions on the motion of the system, we can numerically integrate equation 3.1 after each time step.

For the brachiation system, the equations of motion were generated using a commercially available package called SD-FAST. SD-FAST can generate C or Fortran subroutines for the equations of motion by applying a variant of Kane's method [28] and a symbolic simplification phase. The C subroutines were selected to determine the accelerations, velocities, and positions of each link at each time step given the applied forces and torques. The fixed step size, fouth-order Runga-Kutta integrator, was applied to advance the simulation forward in time to generate related motion sequences.

Chapter 4

Tailored Control

The design of a physically-based animation system is partitioned into four core steps. The first three steps, namely target motion analysis, character model determination and dynamics equation derivation, have already been introduced in the previous chapter. This chapter, introduces the fourth core step, the design of the controller, which is further described and illustrated in the next four chapters.

This chapter focusses on tailored control as one of the controller design methods. After introducing the overview of this method, subsequent sections apply it to a 3-Link model to design tailored 3-Link control to generate brachiation motion sequences followed by the more complex 9-Link tailored control model concentrating on how to generate more natural-looking brachiation. Finally, at the end of this chapter a brief summary, as well as the features of automaticity and controllability that tailored control achieved are reported.

4.1 Overview of Tailored Control

During the past two decades, scientists have been inspired to design a controller using the tailored control method because of its high automaticity. For example, Hodgins et al. [23] used this method to animate diving and human athletics.

Tailored control is feasible based on its two specific features. The first, considering the goal motion from the viewpoint of time and space, regardless of the complexity of a motion sequence, it can be decomposed into several successive sub-sequences. For instance, consider the motion involved in human walking, since almost the whole body's bones, muscles and nerves are involved sequentially, it is very difficult to analyze and control the entire motion as a single indivisible block. On the other hand, if the entire motion sequence is analyzed as several successive phases based on time, and the phase is set properly, it would be easier to design a delicated controller for each phase, and superimpose them rather than design a gross unsuitable control for the whole motion sequence.

The second feature, concerning the controller, especially for those complex models which possesses many degrees of freedom (DOF), the entire system can be hierarchically decomposed into several sub-systems according to their different functions. For example, if we again consider the motion involved in human walking, even in a certain walking phase that is setup in the way described above, many DOFs are involved simultaneously to complete a certain walking gait. It would be more appropriate to focus on controlling the DOFs in a hierarchical way, rather than to contemplate controlling all the DOFs simultaneously and impartially. This means that while concentrating on the motion of the left leg, which is hierarchically constructed by the control of the left foot, the left lower leg and the left upper leg with our second feature, we can hierarchically consider the motion control of the left foot, left lower leg and left upper leg, meanwhile temporarily neglecting the motion control of others, such as the motion control of the head, upper limbs or trunk. This would be an efficient and logical way to deal with a complex model motion.

After simplifying the complete motion into several key phases, and by hierarchically constructing the control, we could obtain the kinematic differences of each DOF between the current phase and the desired phase. For example, within the current phase, the present angle of the k_{th} DOF formed by the $link_i$ and the $link_j$ is θ, while the angular velocity is $\dot{\theta}$. Assume that the angle and angular velocity of the desired phase are θ_D and $\dot{\theta}_D$ respectively, namely the desired angle and velocity. To control the $link_j$ moving from the current phase to the desired phase appropriately, a proportional-derivative control, named PD control, is applied to generate the torque of the DOF_k, τ_k, in the following way,

$$\tau_k = K_P * (\theta_D - \theta) + K_D * (\dot{\theta}_D - \dot{\theta}); \tag{4.1}$$

where the parameter of K_P and K_D are the proportional gain and the derivative gain of this DOF respectively. They are gleaned from experiments. After we calculate the torque of all DOFs, τ, substitute into the dynamics equation, presented in the previous chapter. Then we are able to obtain new updated kinematics data such as positions, velocities and accelerations. If we draw the character frame by frame and with these updating the kinematics data on the screen then we can create the animation sequences. This is the main idea of the tailored control method.

A few researchers are involved in designing swinging up control from the viewpoint of robotics research where the models are constructed with simple models. The main shortcomings of their method is that they do not consider the reality of the swinging up and grasping motion, ie. does it look like a real Hylobate? In this thesis, we delve into the brachiation control problem based on different complexities of the model, a 3-Link and a 9-Link model, from the viewpoint of the phase and hierarchy features of Tailored Control. The reality and natural flow of the motion are also considered.

4.2 3-Link Tailored Control

Naturally, in brachiation the two most important problems are swinging up and grasping. To deal with them in 3-Link tailored control, two controls, swinging-up control and grasping control are designed. Within each control, the control hierarchy is set concisely and precisely as follows, where RAC, TKC and LAC represent right arm control, trunk control and left arm control respectively.

Because RAC contains one DOF, joint J_h, is the passive joint without any active torque applied to it, so the output torque of RAC would be simply set to zero. The following discussion focuses on TKC and LAC.

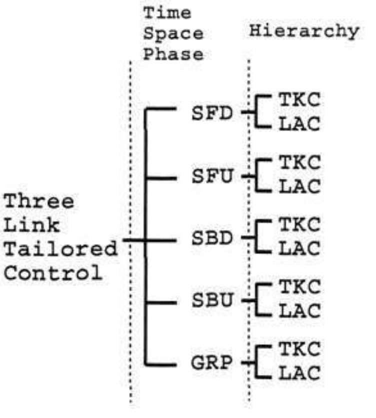


Figure 4.1: The structure of 3-Link tailored control

A general cycle of brachiation contains HLD, SFD, SFU, SBD, SBU and GRP phases, where the four SFD, SFU, SBD and SBU phases are regarded as swinging phases. They aim to pump energy into the system while the last GRP phase is designed to control grasping motion. Hence, there is a profile about 3-Link tailored control, as shown in Figure 4.1. There are five phases included in the tailored control, and each phase contains both LAC and TKC controls.

Since we are considering the SFOG brachiation, as described in Chapter 3, the phases, SFD, SFU and GRP are considered in 3-Link tailored control. Before we illustrate the techniques of designing LAC and TKC for each SFOG phase, the method of measuring the SFOG phase, namely phase control, is first introduced.

4.2.1 Phase Control

Phase control is designed to determine the brachiating phase accurately. Because different phase controllers are different from each other it is important to apply the correct control to each phase.

Determining Swing Phase

The judgement is based on two important terms, the position of the center of mass of the system, COM, and the velocity V of COM, as shown in Figure 4.2.

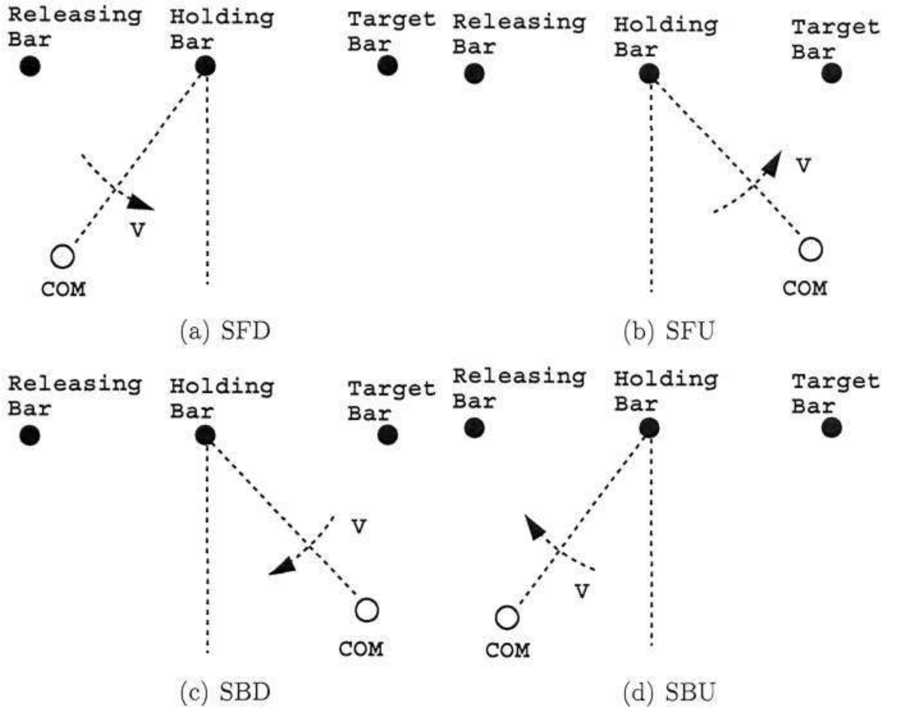


Figure 4.2: Determining the Swing Phases of Brachiation.

When COM is at the left side of the Holding Bar, if the direction of the velocity of COM is swinging forward, then we define this as in the SFD phase, as shown in Figure 4.2 (a). Otherwise, it is in the SBU phase, as shown in Figure 4.2 (d).

When COM is at the right side of the Holding Bar and the level of swinging is not enough, if the direction of the velocity of COM is swinging forward, then we define this is in the SFU phase, as shown in Figure 4.2 (b). Otherwise, it is in the SBD phase, as shown in Figure 4.2 (c).

Determining Grasping Phase

The torque generated by the controller will be incorporated into the dynamic simulation of the left arm only if the palm falls within a circular region defined by a radius with respect to the target bar position, R_{grp}, ie. the collision sensor of the

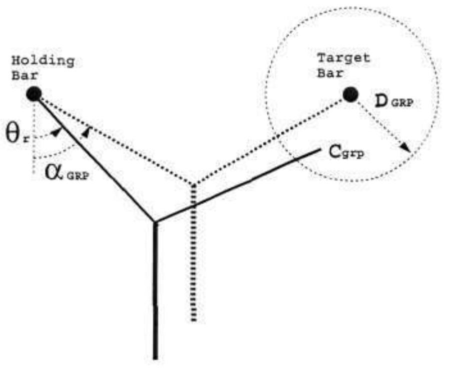


Figure 4.3: Determining 3-Link Grasping Phase.

3-Link model, c_{la} is less than the R_{grp}, or the angular sensor of the right arm angle θ_{ra} reaches a certain pre-specified threshold value, α_{grp}. The meaning of these two alarm attributes can also be seen by referring to Figure 4.3.

4.2.2 Control the Swing-Forward-Down (SFD) Phase

In this phase, the brachiator swings forward down from the beginning or from SBU where the brachiator failed to grasp the target bar in the previous swinging motion. From the viewpoint of energy, the brachiator expects to convert the potential energy of the initiation to the kinetic energy at the end of SFD. The desired gesture of the 3-Link model at the end of SFD, as shown in Figure 4.4, is designed as follow: the brachiator is reaching the lowest level of the whole motion, so the angle sensor of the right arm should be set to zero, and the whole body is swinging forward with a certain velocity. To achieve the requirements, LAC and TKC are designed as follow:

Left-Arm-Control (LAC)

Under this situation, LAC is designed to swing and reach the lowest level of the whole motion duration. The desired angle sensor of the left arm, θ_{Dla}, is zero, and the desired velocity set to a certain value, $\dot{\theta}_{Dla}$, which is determined by experimentation. So the basic PD control equation 4.2 for LAC of SFD is derived as:

$$\tau_{la} = K_{Pla}(-\theta_{la}) + K_{Dla}(\dot{\theta}_{Dla} - \dot{\theta}_{la}); \quad (4.2)$$

where, τ_{la} is the torque applied on Joint J_{la}; K_{Pla}, K_{Dla} are the proportional gain and the derivative gain respectively and $\theta_{la}, \dot{\theta}_{la}$ are the angle and velocity sensors of the left arm link.

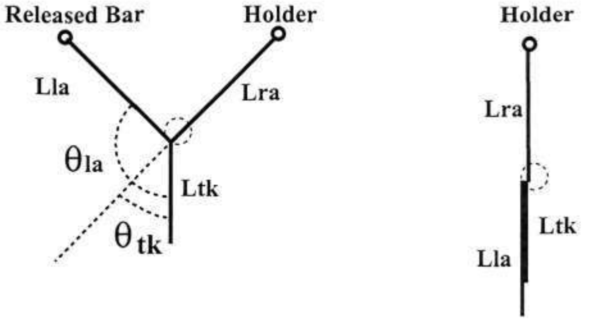


Figure 4.4: The beginning state and the ending desired state of a 3-Link SFD

Trunk-Control (TKC)

TKC is to reduce the angular sensor θ_{tk} to zero to swing the trunk forward reaching the lowest level at the end of the SFD phase with a certain velocity. So the desired angle of the trunk, θ_{Dtk}, is zero, meanwhile, the desired velocity, $\dot{\theta}_{Dtk}$, is determined experimentally. The equation is:

$$\tau_{tk} = K_{Ptk}(-\theta_{tk}) + K_{Dtk}(\dot{\theta}_{Dtk} - \dot{\theta}_{tk}); \quad (4.3)$$

where, τ_{tk} is the torque applied on joint J_{tk}; K_{Ptk}, K_{Dtk} are the proportional gain and the derivative gain respectively and $\theta_{tk}, \dot{\theta}_{tk}$ are the angle and velocity sensors respectively of the trunk link.

4.2.3 Control the Swing-Forward-Up (SFU) Phase

After the SFD phase, the brachiator continues swinging forward and up. In this phase, from the viewpoint of energy, the brachiator expects to convert the kinetic energy obtained from the SFD phase to potential energy. As shown in Figure 4.5, the desired gesture of the 3-Link model at the end of the SFU phase, is designed as: left arm link is trying to swing up to its DOF limit, and this swing motion would benefit the whole body swinging up. Almost at the same time, the trunk remains vertical with the ground. This interesting phenomenon is observed from a variety of Hylobate's performances. The LAC and TKC are designed as below:

Left-Arm-Control (LAC)

During the SFU phase, LAC is designed to control the left arm link to swing forward and up to allow the whole body to swing up. As described in the literature, [72, 73], the rotation range of the Hylobate's shoulder is bigger than that of a human being. Here we simply set it as 180 degrees so that it indicates the desired angle of the left arm $\theta_{Dla} = 180.0$ degrees. When the left arm is reaching the limit angle, we assume the related velocity is zero. If the velocity is not zero, the left arm would swing over. This kind of motion is not useful to the swinging motion. So the desired angular velocity of the left arm within the SFU phase is set to zero, $\dot{\theta}_{la} = 0$. Hence, the LAC equation of SFU is designed as

$$\tau_{la} = K_{Pla}(180.0 - \theta_{la}) + K_{Dla}(-\dot{\theta}_{la}); \tag{4.4}$$

where, τ_{la} is the torque applied on the joint J_{la}, K_{Pla}, K_{Dla} are the proportional gain and the derivative gain respectively; $\theta_{la}, \dot{\theta}_{la}$ are the angle and velocity sensors respectively of the left arm link.

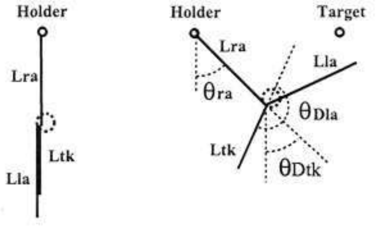


Figure 4.5: The beginning state and the ending state of 3-Link SFU

Trunk-Control (TKC)

To TKC, the hylobate is trying to keep its body perpendicular to the ground, so the desired angle of the trunk is updated according to the angle sensor of the right arm, θ_{ra}, but the value is negative. Meanwhile, the desired velocity, $\dot{\theta}_{Dtk}$, is set to zero to stabilise the whole system. Consequently, the TKC equation is designed as

$$\tau_{tk} = K_{Ptk}(-\theta_{ra} - \theta_{tk}) + K_{Dtk}(-\dot{\theta}_{tk}); \qquad (4.5)$$

where τ_{tk} is the torque applied on the joint J_{tk} in the SFU phase, K_{Ptk}, K_{Dtk} are the proportional gain and the derivative gain respectively; $\theta_{tk}, \dot{\theta}_{tk}$ are the angle and velocity sensors respectively of the trunk link and θ_{ra} is the angular sensor of the right arm.

4.2.4 Control the Grasp (GRP) Phase

One of the challenging tasks is the control of the palm of the left arm for grasping the target bar, because there is no actuator situated at the holding point of the holding arm. As a result, the position of the palm of the grasping arm cannot be directly controlled for grasping the bar precisely. However, the direction of the grasping arm can be controlled using a tailored hand grasping controller.

Left-Arm-Control (LAC)

As the brachiator falls into the GRP phase, LAC intends to control the left arm to grasp the target T in three steps as described below:

1. Dynamically calculate the angle, α, between the left arm and the line ST with the theory of triangular geometry (see Figure 4.6). The angle α is regarded as the desired angle of the left arm. We assume the brachiator could catch the target with little impacting force, so the desired velocity of the left arm is set as zero.

2. To generate a realistic grasping motion, a PD control method is employed to gradually generate appropriate torques at the joint, J_{la}, of the left arm, τ_{la}. To meet the requirement, the following torque expressions are employed in the simulation:

$$\tau_{la} = K_{Pla}(\alpha - \theta_{la}) + K_{Dla}(-\dot{\theta}_{la}); \tag{4.6}$$

3. LAC applies the torque, τ_{la}, on the joint J_{la} to minimise the difference between the angular sensor θ_{la} and the desired angle α obtained from the first step.

Trunk-Control (TKC)

Similar to controlling the left arm to grasp the target with LAC, TKC is applied to control the orientation of the trunk to maintain an appropriate posture. After observing Hylobate's brachiation in nature, we realise that the trunk is almost perpendicular with the ground when it is grasping the target. Consequently, the orientation sensor of the brachiator is reasonably required to be vertical with the ground in the GRP phase. So the desired angle of TK is set as the negative of the angular sensor of the right arm, ie. $-\theta_{ra}$. To stabilise the system, the desired velocity of the trunk is set to zero. The appropriate torque, τ_{tk}, for controlling the trunk in the GRP phase is derived using the following equation,

$$\tau_{tk} = K_{Ptk}(-\theta_{ra} - \theta_{tk}) + K_{Dtk}(-\dot{\theta}_{tk}); \tag{4.7}$$

where τ_{tk} is the torque applied on joint J_{tk}; K_{Ptk}, K_{Dtk} are the proportional gain and the derivative gain respectively and $\theta_{tk}, \dot{\theta}_{tk}$ are the angle and velocity sensors respectively of trunk link, θ_{ra} is the angular sensor of the right arm.

After application of the LAC and TKC of GRP, the brachiator is controlled to approach the target with an appropriate gesture. The trunk link is perpendicular with the ground. As the collision sensor of the 3-Link model is less than a predefined value, we consider the brachiator catches the target successfully.

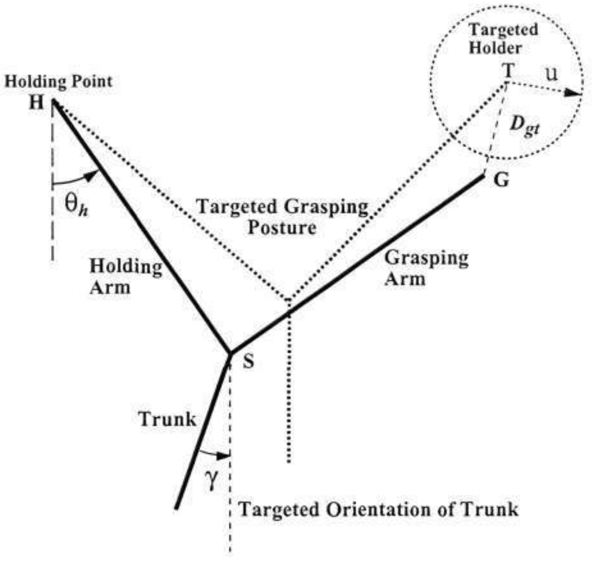


Figure 4.6: 3-Link Grasping Control.

4.3 9-Link Tailored Control

Since the 9-Link model is more complex than the 3-Link model, which implies 9-Link tailored control should be more sophisticated. From the viewpoint of control hierarchy, four controls are required: Hold-Arm-Control (HAC), Trunk-Control (TKC), Grasp-Arm-Control (GAC) and Lower-Limb-Control (LLC). In the HAC, two DOFs are controlled, J_{rua} and J_h, as shown in Table 4.1. Since J_h, a passive joint, is the only point which connects and interacts with the exterior environment through the holding bar, the output of the control of J_h is zero. We consider it a tractable simplification where the friction between the right palm of the brachiator and the holding bar is ignored. So in this control only J_{rua} is considered.

Control	Joint	Link
HAC	J_{rua}, J_h	RUA, RLA
TKC	J_{trk}	TRK
GAC	J_{lua}, J_{lla}	LUA, LLA
LLC	J_{lul}, J_{lll}, J_{rul}, J_{rll}	RUL, RLL, LUL, LLL

Table 4.1: Hierarchical control classifies all DOFs by their distinct functions: Holding Arm Control (HAC), Trunk Control (TKC), Grasp Arm Control (GAC) and Lower Limbs Control (LLC).

Although trunk control, TKC, it only controls the trunk link, it is very important to the whole system, where the DOF of the trunk link, J_{TRK} is the pivot of the system connecting with other link controls, the upper limbs, HAC, GAC and the lower limbs, LLC. It is a critical problem to control the trunk link properly to swing up and grasp the target effectively with an appropriate gesture.

Grasping arm control, GAC, contains two subsystems, the left lower arm control, LLAC and left upper arm control, LUAC. The GAC possesses two different purposes: first, when the magnitude of swinging is not enough, the control intends to pump energy into the system by swinging the left arm properly and, second, it controls the left upper arm and left lower arm to approach and grasp the target bar when swinging is adequate.

Lower limb control, LLC, comprises four sub-systems: left lower leg control, LLLC, left upper leg control, LULC, right lower leg control, RLLC and right upper leg control, RULC. The purpose of LLC is to control the lower limbs to achieve the required posture as well as pump energy into the system by adjusting the posture properly.

From the viewpoint of motion phase, a general brachiation includes one HLD phase, four swing phases (SFD, SFU, SBD and SBU) and one GRP phase. Since we focus on SFOG brachiation, 9-Link tailored control contains HLD, SFD, SFU and GRP controls, as shown in Figure 4.7.

From the viewpoint of the control level, three level controls are contained: phase control, state control and PD control. The phase control is designed to determine the present motion phase. The state control characterises the desired kinematic data for each brachiation phase. The PD control applies the results of the state control to calculate the appropriate torques for tailored control. They are illustrated below.

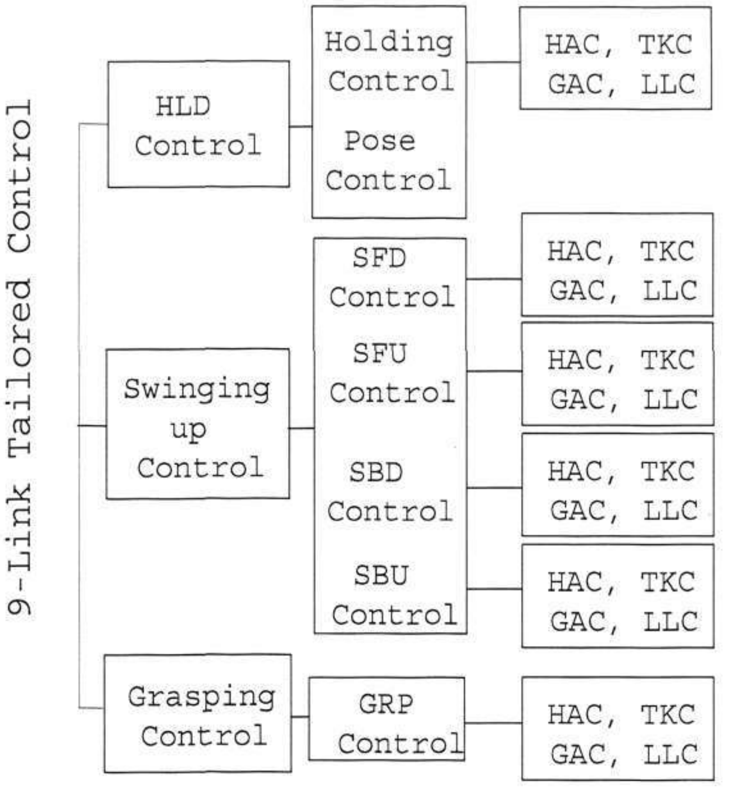


Figure 4.7: 9-Link Brachiation control contains swing control, grasp control and initial control. In 9-Link swing control, there are four controls, SFD, SFU, SBD, SBU controls. These four controls, 9-Link grasp control and 9-Link pose control contain four sub controls, Hold-Arm-Control (HAC), Trunk-Control (TKC), Grasp-Arm-Control (GAC) and Lower-Limb-Control (LLC).

4.3.1 Phase Control

9-Link Phase control is designed to determine the brachiating phase accurately. A complete brachiation contains the six phases HLD, SFD, SFU, SBD, SBU and GRP. The First HLD phase is easy to identify because it is the starting phase. The following four phases, SFD, SFU, SBD and SBU are about swinging. The final phase is about grasping. The technique for determining the swinging up phases is similar to 3-Link tailored control which is based on the position of the center of mass (COM) of the 9-Link system and the direction of COM.

The method of determining the GRP phase is achieved by two measurements, one is the alert angle (Θ_{GRP}) and the other is the distance (D_{GRP}), as shown in Figure

4.8. The alert angle can be computed using triangular geometry theory. The alert distance can be set as a radius with center at the target bar. When the angle sensor, θ_{grp} is beyond Θ_{GRP}, or the collision sensor C_{lla} is less than the D_{GRP}, the phase changes into GRP.

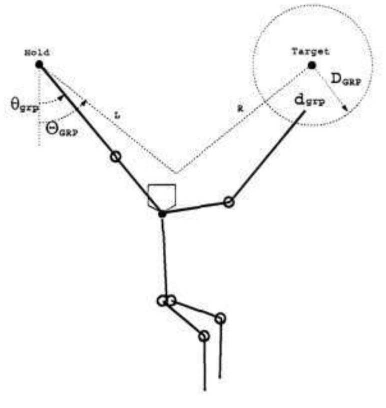


Figure 4.8: 9-Link Phase Control: GRP

4.3.2 State Control

The state control is to calculate the desired kinematics data of each DOF according to the different features of the different phases. The desired angles of each phase were described in Chapter 3 and the relevant figures are shown in Figure 3.3. The desired angular velocities are derived according to the experiments. The controls are detailed below from SFD, SFU to GRP. The special phase HLD is introduced.

Control the Swing-Forward-Down (SFD) Phase

At the beginning of the SFD phase, the potential energy should be at a high level, meanwhile the velocity of the COM should be zero, hence the kinetic energy of the system should be zero. At the end of the SFD phase, these conditions are reversed, the brachiator reaches the lowest level of brachiation which indicates that the potential energy is at the lowest level. Conversely, the kinetic energy is increasing to the greatest level as the velocity of COM reaches the greatest. On the gesture side, to ensure the lowest level of brachiation is achieved, the brachiator stretches the body to let the COM be as low as possible. The related kinematics features are detailed in Table 4.2.

Control	Link	Function	Desired Angles
HAC	RUA	Stretch the right-up-arm straight.	0
TKC	TRK	Control trunk approaching the lowest level.	0
GAC	LUA LLA	Swing left arm (upper and lower) to lowest position at the end of SFD.	0 0
LLC	RUL LUL RLL LLL	Ensure the lower limbs reach the lowest level through extending both legs.	0 0 0 0

Table 4.2: Kinematic data of Swing-Forward-Down (SFD).

Control the Swing-Forward-Up (SFU) Phase

At the beginning of SFU, the brachiator is swinging at the lowest level, so the potential energy should be at the lowest level. Meanwhile, at the moment the brachitor starts SFU, ie. the end of SFD, the kinetic energy of the system should reach the highest level. On the gesture side, the brachiator stretches the whole body, including the trunk, upper limbs and lower limbs. At the end of SFU, the velocity of the brachiator achieves a certain value. This value is determined by the experiments. Meanwhile the potential energy reaches the higher level during the SFU phase by swinging the right arm pointing to the target bar, hence directly pulling the body higher, and withdraws the lower limbs, as well as swinging the left arm up and forward. These are detailed in Table 4.3.

Control the Grasp (GRP) Phase

When the swinging-up is sufficient, the grasp control is aroused. In the grasp phase, the brachiator intends to catch the target bar using the grasping arm with a natural looking gesture. These are detailed in Table 4.4.

Control	Link	Function	Desired Angles
HAC	RUA	Stretch right-up-arm straightly.	0
TKC	TRK	Control trunk perpendicular to the ground.	Calculated according to the posture of RUA.
GAC	LUA	Swing left arm to point target bar.	Calculated from geometry of shoulder position, trunk angle, and target position.
	LLA	Stretch left-lower-arm straightly.	0
LLC	RUL	Curl up the left leg and the right leg to pull up the level of COM.	45
	LUL		45
	RLL		-45
	LLL		-45

Table 4.3: Kinematic data of Swing-Forward-Up (SFU).

Control	Link	Function	Desired Angles
HAC	RUA	Stretch right-up-arm straightly.	0
TKC	TRK	Control trunk perpendicular to the ground.	Calculated from geometry.
GAC	LUA LLA	Swing both lower and upper left arm to grasp target.	Calculated from geometry.
LLC	RUL	Curl up the left leg and the right leg to pull up COM further.	90
	LUL		90
	RLL		-90
	LLL		-90

Table 4.4: Kinematic data of Grasp Phase (GRP).

Holding (HLD) Phase Control

Observing a hylobate's brachiations in nature, it is not difficult to discover an interesting phenomenon: after a brachiator starts its brachiation, it may hold the bar(s) with both of its palms and adjust its posture, ie. swinging its body backward, then releases its holding arm and starts a general brachiation (see Figure 3.1 (a)-(e). We realise that this kind of initial motion is very useful to brachiation. First, before action starts, if the brachiator could store more potential energy, then it will brachiate more efficiently. Swinging the body backward and pulling the legs up would pull up the COM of the whole body increasing the total potential energy. Second, it is an unstable state to do any action with only one arm holding under the effect of the gravity. When both arms are holding bars, it is more convenient for the brachiator to control the gesture of the body and begin a brachiation.

To animate this initial motion with the tailored control method, we design a HLD control that contains a holding-bar control and a posture control. These are presented below.

Holding-Bar Control

In holding-bar control, as shown in Figure 4.9, we apply a PD controller on the left palm to hold the bar. The three values of the vector PB along X, Y and Z axes are V_x, V_y and V_z. The velocities along the three axes are $\dot{V}_x, \dot{V}_y$ and $\dot{V}_z$. The forces, F_x, F_y and F_z, are derived using Equation 4.9,

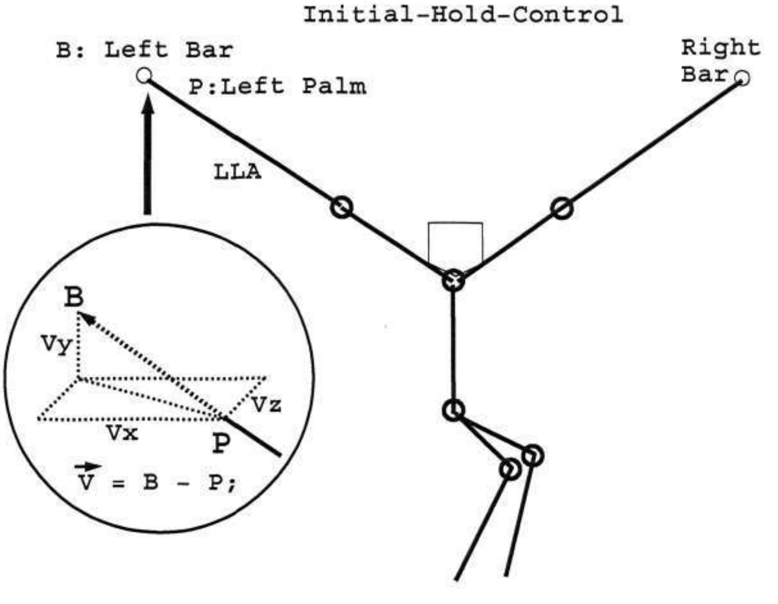


Figure 4.9: 9-Link HLD Control: Holding-Bar Control

$$V = B - P; \tag{4.8}$$

$$\begin{aligned} F_x &= P_{xhold}V_X + D_{xhold}\dot{V}_X; \\ F_y &= P_{yhold}V_Y + D_{yhold}\dot{V}_Y; \\ F_z &= P_{zhold}V_Z + D_{zhold}\dot{V}_Z; \end{aligned} \tag{4.9}$$

In this work, the motion is restricted to 2D, hence $F_z = 0$.

Posture Control

In posture control, when holding two bars with both left and right palm, the brachiator is designed to pull the COM back and upward. This is achieved by movement in all links, as shown in Figure 4.5. The relevant controls, HAC, TRK, GRC and LLC, are detailed in Table 4.5.

Control	Link	Function	Desired Angles
HAC	RUA	Keep holding arm straight.	0
TKC	TRK	Control TRK to swing backward.	A certain experimental value.
GAC	LUA LLA	Shrink left arm to pull whole body up.	Set by experiments.
LLC	RUL LUL RLL LLL	Curl up the left leg and the right leg to pull up COM further.	90 90 -90 -90

Table 4.5: Kinematic data of the posture control.

4.3.3 PD Control

The PD control applies the desired angles and angular velocities of each control calculated by state controls or empirical values, and the present angular sensor and velocities to calculate the torques. This is achieved by proportional-derivative control:

$$\tau_i = K_{Pi}(\theta_{Di} - \theta_i) + K_{Di}(\dot{\theta}_{Di} - \dot{\theta}_i); \tag{4.10}$$

where τ_i is the torque for the i_{th} DOF. θ_i and $\dot{\theta}_i$ are the angular sensor and velocity of the i_{th} DOF. θ_{Di} and $\dot{\theta}_{Di}$ are the desired angle and velocity of the i_{th} DOF. K_{Pi} and K_{Di} are the proportional gain and the derivative gain of this DOF respectively.

4.4 Summary

In this chapter, we first briefly introduced the general idea of tailored control. It's two features, hierarchical and time space, are examined in this thesis to analyse and design brachiation tailored control.

Using tailored control for the under-actuated and extremely unstable brachiation system is totally different from other existing motion style control systems which use the tailored control.

Based on the threads of the idiosyncrasies, the 3-Link brachiation tailored control is presented for different phases and different hierarchies. The 3-Link tailored control attempts to control the trunk motion which is very important to the brachiation and ignored by the previous researchers. Furthermore, to animate more natural looking brachiation motion, 9-Link brachiation tailored control is achieved for the first time. The special state of brachiation, HLD phase, has been revealed and the related control, HLD phase control, developed.

Through developing the tailored control for brachiation, we realise that automaticity of tailored control has been improved compared with the kinematic key-frame control. It can automatically accommodate the physical condition, for example gravity, into the system design so that the generated motion is physically true, which is a very difficult and tedious task using the traditional key-frame method. Controllability on the other hand, is not satisfactory. Although we can adjust the desired kinematics data during the design, it is not easy for the general animator to apply this method to produce various different styles of motion.

In the next chapter, a more automatic control method, heuristic control for brachiation is described.

Chapter 5

Heuristic Control

In the previous chapter, it was concluded that the automaticity of tailored control is an improvement when compared with the kinematics key-frame technique. There is another way to improve automaticity of physically-based animation control which applies artificial intelligence (AI) techniques to design controls.

Several researchers [12, 5, 4, 19] have attempted to solve the problem of generating swinging up trajectories within the scope of robotics. There are two major disadvantages of these previous attempts. First, their research was based on simple models, and the connections of the links were in series. For instance, for a three links model, the first link represents a holding arm, the second represents a trunk while the third link represents a lower limb as well as a grasping arm. With models which are too simple it is impossible to perform convincing motion sequences. Connecting links in series is not the best solution to brachiation. The link between the trunk and the grasping arm are both important during brachiation motion. However, they cannot be effectively demonstrated using two or three links connected in series. This indicates a more complex model which is connected in parallel is necessary. The previous methods also concentrated on the swinging up functions. The posture related to realistic and natural looking motion during swinging up was ignored. Posture is obviously important to animation and should not be ignored.

In this thesis, a heuristic control method (HC), as an example of AI Control, is investigated. It can automatically and heuristically generate appropriate torque to optimise the brachiation according to objective functions. The models are based on different complexity models, one is a 3-Link parallel connected model and the other is a more sophisticated 9-Link parallel model.

Below, an overview of heuristic control is given, followed by the illustration of 3-Link heuristic control and 9-Link heuristic control. The chapter concludes with a brief summary.

5.1 Overview of Heuristic Control

The core issue in the design of heuristic control of a physically-based brachiation system is focusing on how to generate appropriate torque or force in the various sections of the model. The torque or force should solve not only the problem of swinging up effectively, but also create realistic motion in the heuristic control. As shown in Figure 5.1, the torques or forces generated by heuristic control are passed to the dynamics platform to calculate the kinematic data for the brachiator, including angles, velocities and accelerations. The motion producer module accesses this kinematic data and draws the image on the screen frame by frame to generate the expected animation sequences.

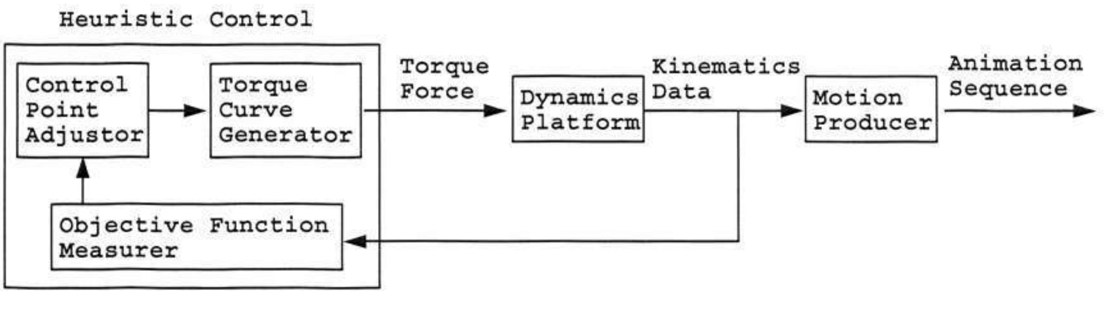


Figure 5.1: Heuristic Control Overview

Within the heuristic controller, three modules are included: the control point adjustor, the torque curve generator and the objective function measurer. They are briefly introduced below.

Control Point Adjustor

The period of applied heuristic control is generally divided into several equal parts (say n-1 parts with n control points determined by experimentation). The control point adjustor is designed to adjust the values of these control points, allowing increase or decrease of the values according to the control strategy.

Torque Curve Generator

When any control point is adjusted, the torque curve generator will be called to reconstruct the torque curve based on the new set of control points. The torque curve reconstruction method adopted in this work is the B-Spline method.

Objective Function Measurer

After adjustment, the control points and the related torque curve are passed to the dynamics platform. The Objective Function Measurer determines whether the adjusted result is better or worse.

Adjusting a control point, regenerating the torque curve and measuring the result are accomplished in a single loop. An optimum result is obtained by performing iterations of this loop, making adjustments to the control point and using the Objective Function Measurer as the criterion.

Three measurement terms are used, the energy term $E(t)$, gesture term $G(t)$ and collision term $D(t)$. The $E(t)$ measures the conversion between potential energy and kinetic energy. $G(t)$ measures the difference between the desired gesture and the current gesture, as described in Equation 5.1

$$G(t) = \sum_{i=1}^{N} \mid \Theta_{Di} - \theta_i(t) \mid \tag{5.1}$$

where Θ_{Di} is the desired angle of the i_{th} DOF; N is the entire number of DOF, here N is the max number of degrees of freedom of the system; and θ_i is the angular sensor of the i_{th} DOF.

The collision term, $D(t) = C_{lla}(t)$ (collision sensor), measures the grasping result through monitoring the distance between the target bar and the palm of the grasping hand.

5.2 Heuristic Control Algorithm

The algorithm for heuristic control is as follows. Suppose there is a system with m DOFs, and n control points. Heuristic control will start the control from adjusting the i_{th} DOF's j_{th} control point by, say, increasing $p_{i,j}$, the control point set of i_{th} DOF, p_{i0} to $p_{i,n-1}$, are passed to the torque curve generator to generate a new torque curve, $T_i(t)$. The new set of torques are transferred to the dynamic equation to calculate the kinematic data of the system.

At the end of the control interval, the final result of the adjustment is measured by the objective function measurer. If the result is better, the control point adjuster will continue to adjust this control point in the previous way, by increasing the value of control p_{ij}. Otherwise, if this adjustment is not the first time, stop at this control and continue to the next control point. If the first increasing adjustment is rejected, heuristic control would consider that the increasing adjustment is not a good choice and after restoring the original value of the control point it starts to decrease adjustment. The strategy of the decreasing adjustment is similar to that for the increasing adjustment.

To the same control point, no matter the increasing or decreasing adjustment, heuristic control would only adjust this control point at certain times even though the last measured result is better. It will never exceed this time to guarantee control efficiency. After finishing this control point, heuristic control will start the next DOF's j_{th} control point, $p_{i+1,j}$, rather than the next control point of the same DOF, $p_{i,j+1}$.

This is called the parallel-prior strategy.

After all the DOF's control points have been adjusted, heuristic control starts to check whether any control point's change during the increasing adjustment or the decreasing adjustment has been accepted. If it is false, heuristic control considers that the current set of control points are the best solution that the present objective-function and strategy can find and no better solution exists. Otherwise, heuristic control will start a new round of adjustment from the first DOF's first control point to the last DOF's last control point within the control interval.

The parameters applied in the heuristic control are hand tuned based on empirical observation. We need adequate enough parameters in heuristic control rather than optimum parameters. Hence the parameters applied in the heuristic control are not guaranteed to be the best set.

5.3 3-Link Heuristic Control

In this section, details of how to apply heuristic control to a 3-Link model is introduced. Here, the 3-Link model is different from the previous researchers' models which were constructed in a series manner. The model here is formulated in a parallel manner, as explained in chapter 3. Below, 3-Link heuristic control is illustrated with a strategy and objective function measurer, which are the core parts of heuristic control.

5.3.1 Strategy of 3-Link Heuristic Control

The strategy of 3-Link heuristic control is based on the concept of Phase-Heuristic-Control (PHC), which means the control interval is set as phase to phase. The major advantage of PHC is that it provides a tool to control the posture of each phase.

For example, to control the SFU phase, we should first finish the SFD phase using heuristic control. After loading the relevant control points of the SFD phase into the system, then start the SFU phase, say from control point i to j (suppose control points 0 to i-1 belong to the SFD phase, and after control point j they belong to the GRP phase).

There are two controllable DOFs, TK and LA, and n control points contained in the 3-Link heuristic control. To each DOF's control point, heuristic control applies the strategy of the increasing or decreasing module described in the previous section, until no better set of control points can be obtained.

From the previous descriptions, we can conclude that there are two loops embedded in 3-Link heuristic control, namely the DOF control loop and the interval control loop. The DOF control loop means that if the measuring result of adjusting the i_{th} DOF is better, then heuristic control would continue adjusting the same DOF in a limited loop, not exceeding a certain time. The interval loop refers to any control point that have been adjusted by applying heuristic control from the starting control point i to the ending control point j within this control phase, and heuristic control will restart from the i_{th} control point to the j_{th} control point again, until there is no more change during the last control loop.

5.3.2 Objective Function Measurer of 3-Link HC

The objective function measurer is another core part of the heuristic control which is directly related to whether the brachiator can swing up and grasp the target smoothly and naturally.

In 3-Link heuristic control, we follow the PHC strategy which indicates that the different phase is measured using a different objective function. We present each objective function according to each different motion phase. Since the feature of each phase is detailed in Chapter 3, the focus here is on the objective function design .

Swing-Forward-Down SFD

In this phase, the objective of the motion is to extend the body to push down the COM. From the viewpoint of energy, the brachiator utilises gravity to convert the potential energy to kinetic energy. So the kinetic energy will be the majority of the objective function, however it is insufficient. The brachiator would move any of it's links vigorously to increase the kinetic energy. However, this kind of movement may not be useful for brachiation. Although the whole system's kinetic energy is increased, the motion effect has not been improved. Moreover, the posture is not natural and realistic. To solve this problem, we add the posture element into the objective function. The desired posture of the brachiator, when it reaches the end of the SFD phase, should be that the angular sensors of TK and LA are zero. The objective function is described as:

$$M_{sfd}(t) = P_E E_K(t) - P_A G(t) \tag{5.2}$$

where P_E and P_A are positive parameters, $E_K(t)$ is the systems kinetic energy function, and $G(t)$ is the gesture function described in equation 5.1.

The first part of equation 5.2 considers the aspect of kinetic energy, the greater the better, while the second part concerns the posture aspect. If the brachiator's posture is different from the expected posture described above, the second part of the equation reflects this fact, so the less difference, the better. From this equation, we can conclude that a greater $M_{sfd}(t)$ is better.

Swing-Forward-Up (SFU)

In this phase, the objective of motion is to contract the body to pull up the COM. From the viewpoint of energy, the brachiator overcomes the effect of gravity to convert kinetic energy to potential energy to swing to a higher level. So the potential energy will be the majority of the objective function. Additionally, the posture aspect is also considered. From observing a video sequence of a hylobate's brachiation, for example, [40] as shown in Figure 3.1 (i), we can conclude that the trunk of the brachiator remains perpendicular to the ground in this phase. We'd like to set this posture to be our goal. The objective function is described as:

$$M_{sfu}(t) = P_P E_P(t) - P_A G(t) \tag{5.3}$$

where P_P, and P_A are positive parameters of potential energy and gesture function.

The first part of equation 5.3 considers the aspect of energy, where the more potential energy the better, while the second part concerns the posture aspect. If the brachiator's posture is different from the expected posture described above, the second part of the equation penalises the relative difference, so the less difference the better. From this equation, we can conclude that a greater $M_{sfu}(t)$ is better.

Grasp Phase (GRP)

Obviously, the major goal of this phase is to reduce the distance between the hand and the target to zero. Meanwhile, from observing the hylobate's brachiation, when it is grasping the target, the trunk is always perpendicular to the ground. The advantage is that it is convenient to start the next swing without adjusting the body. Considering these two aspects, the relative equation is designed as:

$$M_{grp}(t) = P_C C_{la}(t) - P_A G(t) \tag{5.4}$$

where $C_{la}(t)$ is the collision sensor for measuring the distance between the target and the grasping hand, and P_C is a positive parameter for the collision sensor.

The first part of equation 5.4 considers the aspect of the collision sensor, the lower the value the better. The second part concerns the posture aspect. If the brachiator's posture is not perpendicular to the ground as described above, the second part of the equation penalizes the relative difference, so less difference is better. From this equation, we can conclude that a lower value of $M_{grp}(t)$ is better.

5.4 9-Link Heuristic Control

The structure of the 9-Link model system is much more complex than the 3-link model. As the number of links increases, the interaction between the links becomes more significant. Adjusting a control point of the 9-Link model would not only affect the motion of the link, but also the whole body's motion. Taking into consideration the specification of the 9-Link model and the results of previous research in 3-Link heuristic control [72], [73], three versions of the 9-Link heuristic control, namely Phase HC (PHC), final-target HC (FHC) and phase-final-target HC (PFHC) were investigated. These are described in the following sections.

5.4.1 Phase Heuristic Control (PHC)

Phase heuristic control, PHC, which is similar to 3-Link heuristic control is essentially gain-scheduling algorithm. It heuristically adjusts the control points of each phase based on the result at the end of the phase. After completing each phase, PHC starts on the next phase until the GRP phase is reached.

As shown in Figure 5.2, to control phase K, we assume the starting and ending control points are i_{th} and j_{th} respectively. We should first finish all the previous phase control, and load those control points, 0_{th} to $i-1_{th}$, into the system, then start phase K control. The result at the end of phase K is measured and used as the test criterion.

Since the purposes of the various phases are quite different, so the objective functions of each phase are different. The objective functions are presented below according to the different phases, ie. SFD, SFU and GRP.

Swing-Forward-Down (SFD) Phase

In this phase, from the viewpoint of energy conversion, the brachiator should convert the potential energy to kinetic energy. The more kinetic energy that it obtains at the end of SFD, the higher the position it could achieve in the SFU phase. The

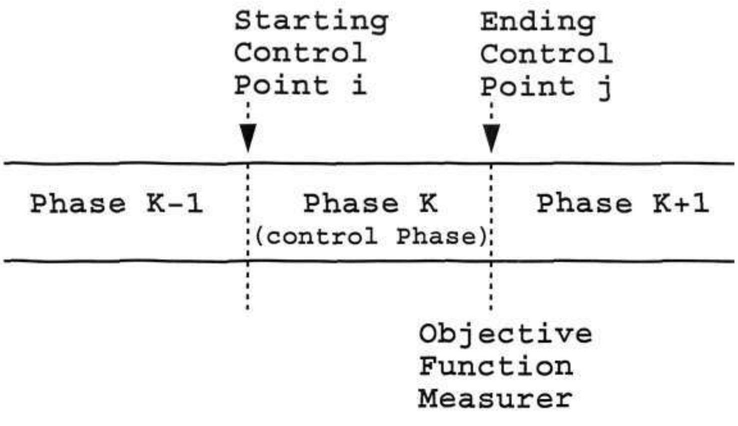


Figure 5.2: 9-Link Phase heuristic control.

energy term, $E(t)$ is measured as $E(t) = K(t)$, where $K(t)$ is the system kinetic energy function.

From the viewpoint of motion gesture, the desired angles of gesture function $G(t)$, as used in Equation 5.1, are designed to achieve the requirement.

The objective function of SFD, $M(t)$, is given in Equation 5.5.

$$M(t) = E(t)K_{eSFD} - G(t)K_{gSFD} \tag{5.5}$$

where K_{eSFD} and K_{gSFD} are the positive parameters of energy measurement and gesture measurement respectively.

Swing-Forward-Up (SFU) Phase

In the SFU Phase, the brachiator tries to swing forward-up toward the target bar. From the viewpoint of energy conversion, it should convert the kinetic energy obtained in the SFD phase to the potential energy, $P(t)$. In other words, it tries to swing higher. The energy term of the objective function, $E(t)$ is measured as $E(t) = P(t)$.

From the viewpoint of motion posture, the desired angles $\Theta_{Di}(i \in [1, 9])$ of the gesture function $G(t)$ are designed to achieve the requirement as described in Section 3.1. For instance, link TRK should be vertical with the ground, the desired angle of TRK, Θ_{Dtrk}, is calculated according to geometry.

The 9-Link SFU objective function, $M(t)$, contains two aspects, energy $E(t)$ and gesture $G(t)$ as given in Equation 5.6.

$$M(t) = E(t)K_{eSFU} - G(t)K_{gSFU} \tag{5.6}$$

where K_{eSFU}, K_{gSFU} are the parameters of Energy Measurement and Gesture Measurement of the SFU phase respectively.

Grasp (GRP) Phase

The goal of the GRP phase is to catch the target bar with correct posture. The objective function of this phase contains the collision term, $D(t)$, and the gesture function, $G(t)$. The desired angles within $G(t)$ are designed according to the GRP features.

The 9-Link swing forward-up objective function, $M(t)$, is given in Equation 5.7.

$$M(t) = D(t)K_{dGRP} + G(t)K_{gGRP} \tag{5.7}$$

where K_{dGRP}, K_{gGRP} are the parameters of collision sensor and gesture measurement respectively. They are positive constants.

5.5 Final-Target Heuristic Control (FHC)

PHC heuristically adjusts the control points based on phase to phase motion. Differing from PHC, final-target HC (FHC), adjusts the control points from the beginning to the end when the brachiator successfully catches the target, as shown in Figure 5.3.

Hence only one objective function is needed for FHC. It tries to reduce the output of the collision sensor to zero with an anticipated posture. Thus there are two terms in the FHC objective function, the collision term, $D(t)$, and the gesture term, $G(t)$, where the desired angles of grasping posture are determined as in the GRP phase of FHC.

The objective function of FHC, $M(t)$ is described in Equation 5.8:

$$M(t) = D(t)K_{dFHC} + G(t)K_{gFHC} \tag{5.8}$$

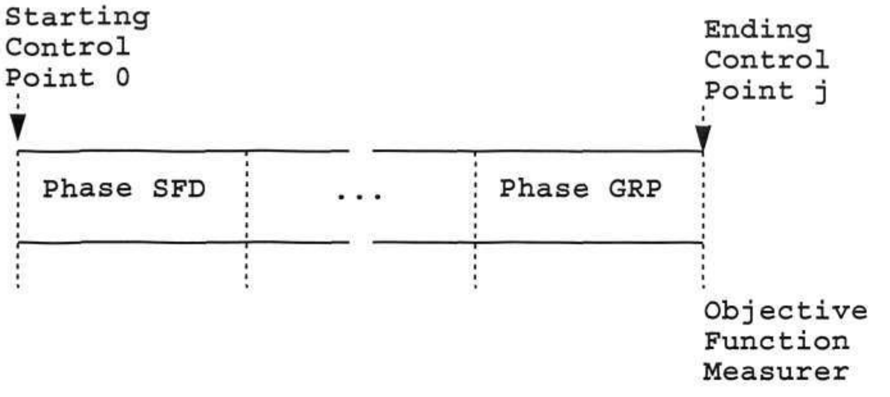


Figure 5.3: 9-Link Final-target heuristic control.

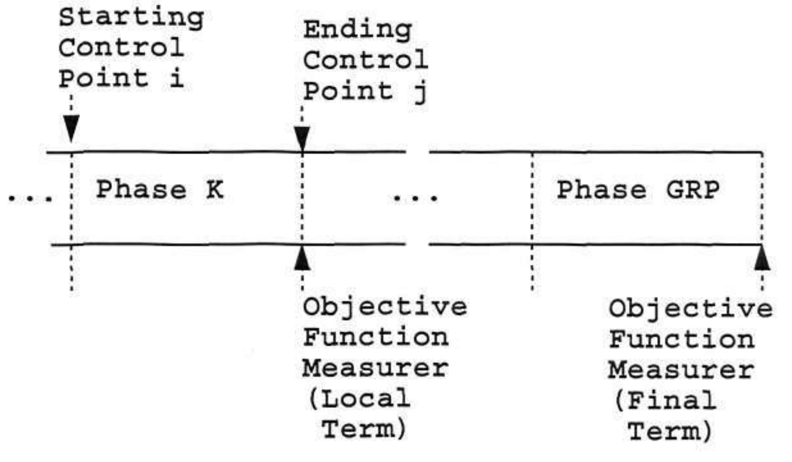


Figure 5.4: 9-Link Phase-final-target heuristic control.

where, K_{dFHC}, K_{gFHC} are the parameters of collision measurement and gesture measurement of FHC respectively.

5.6 Phase-Final-Target Heuristic Control (PFHC)

PFHC, which synthesizes PHC and FHC and adjusts the control points from one phase to another phase, is similar to PHC, rather than the total motion interval, as in FHC. However, PFHC adjusts the control points of each phase, say phase K, as shown in Figure 5.4, not only by measuring this phase's objective, but also the final target objective. From this point of view, PFHC is similar to FHC. The objective functions for each phase are described below according to the different phases.

Swing-Forward-Down (SFD) Phase

In this phase, there are two terms in the objective function, the local gesture term, $G(t)$, and the final collision sensor term, $D(t)$.

Instead of the energy concept of PHC's SFD control, we adopt a final collision term that indicates the grasping effect, $D(t)$. Because the eventual aim of converting more potential energy to kinetic energy is to swing higher at the SFU and GRP phases, the $D(t)$ is a more direct indicator of the effect of SFD. The gesture term is similar to PHC's SFD gesture term.

The SFD objective function of PFHC is given in Equation 5.9:

$$M(t) = D(t)K_{dPFHC} + G(t)K_{gPFHC} \tag{5.9}$$

where K_{dPFHC}, K_{gPFHC} are the parameters of Collision Term and Gesture Term of the SFD objective function of PFHC respectively.

Swing-Forward-Up (SFU) Phase

There are two terms in the objective function, the local gesture term, $G(t)$, and the final collision term, $D(t)$. The gesture term is similar to PHC's SFU gesture term. Meanwhile, $D(t)$ is the same as the $D(t)$ term of SFD in PFHC.

The SFU objective function of PFHC is given in Equation 5.10:

$$M(t) = D(t)K_{dPFHC} + G(t)K_{gPFHC} \tag{5.10}$$

where K_{dPFHC}, K_{gPFHC} are the parameters of Collision Term and Gesture Term of SFU objective function of PFHC respectively.

Grasp (GRP) Phase

The two terms in the GRP objective function, the gesture term $G(t)$ and the collision term $D(t)$, are the same as $G(t)$ and $D(t)$ in the GRP of PHC phases. The GRP objective function of PFHC is given in Equation 5.11:

$$M(t) = D(t)K_{dPFHC} + G(t)K_{gPFHC} \tag{5.11}$$

where K_{dPFHC}, K_{gPFHC} are the parameters of Collision Term and Gesture Term of GRP objective function of PFHC respectively.

5.7 Summary

In this chapter, we designed heuristic control for a 3-Link brachiator model, where the model was constructed using parallel connections. We keep considering how to effectively control swinging and grasping motion, and we are also concerned with how to produce realistic and natural-looking motion.

Based on the research of 3-Link heuristic control, a sophisticated 9-Link heuristic control that contains phase heuristic control, final-target heuristic control and phase-final-target heuristic control is developed. Phase heuristic control can assist the animator to control medium posture during brachiation, meanwhile requiring accurate parameters to realise grasping of the target. Whether the brachiator could swing up and grasp the target or not is based on the energy conservation. The relation between the energy term and the gesture term in the objective function is very sensitive.

The final-target heuristic control is a more direct way to realise the grasp task, because the task, finally grasping the target, is directly embedded in the objective function. On the other hand, the medium gesture, for instance SFD or SFU, cannot be handled.

The phase-final-target heuristic control synthesises the advantages of both PHC and FHC, as it considers the medium posture and also concerns the final task to grasp the target. This should be the better method for brachiation.

3-Link and 9-Link heuristic control can generate appropriate torque for brachiation. To the final user, after all parameters and controllers have been set up, the system would automatically generate the brachiation motion sequence which implies that the automaticity from this viewpoint is quite high. However, after the controller and parameters are determined, it is very hard for a final user to generate different styles of brachiation motion. This indicates an unfortunate fact that heuristic control has very low controllability.

Chapter 6

Interactive Control

Both tailored control and heuristic control possess relevant high automaticity, however the controllability is quite low. In actual production work, high controllability is required. In this chapter, high controllability interactive control is presented.

Interactive control is inspired by two special abilities of humans. The first is the perception which allows a person to detect a small amount of unusual movement in a motion sequence. The second is the adaptation. For instance, when we played swing games in our childhood, we did not know any physics, but through trial-and-error adaptation, we realised the regulation of swing and played very well.

6.1 Overview of Interactive Control

The purpose of interactive control is to intuitively provide animators with a tool to produce physically-based animation by interactively adjusting torques or forces. Both continuous and discrete adjustment can be handled. The overall process of interactive control is shown in Figure 6.1. The generated torque or force is passed to the Dynamics-Platform to calculate the related kinematics data. The animation producer module receives the data and draws on the screen to generate the desired animation. The animator reviews the animation, and if it is not satisfactory, readjustments are made.

Interactive control contains several important control modules as shown in Figure

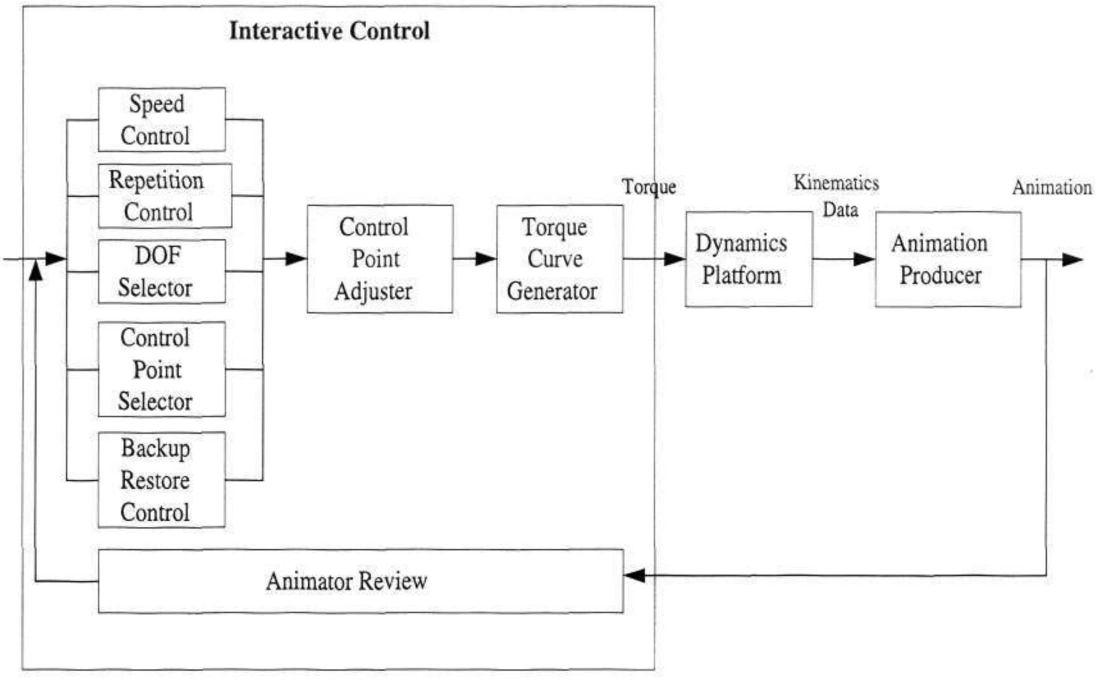


Figure 6.1: Overview of Interactive Control

6.1 : speed control, repetition control, DOF selector, control point selector, backup-restore control, control point adjustor and torque curve generator. These modules are described below.

6.2 Modules in Interactive Control

Animation Speed Control

Since interactive control is based on the animator's perception, the motion speed is critical. Here the motion speed refers to the playback speed of the motion. Using just one constant speed during the entire adjustment is insufficient. It is reasonable to set different speed levels according to the different conditions. When an animator is observing and perceiving the motion it is time to speed up. When the animator starts to adjust the control points it is time to slow down. The actual speed is dependent on the judgement of the animator.

Repetition Control

A desired solution is usually gleaned through step by step adjustments, rather than through one-time adjustment. Repeating the simulation of the motion from the beginning to the end several times may waste time. Through repetition control, the animator can define the repetitive interval where adjustments are needed via the keyboard or menu-based interface. The system will only loop within this interval until the new repetition interval is set up. After applying repetition control, time is saved and the efficiency is improved.

Backup-restore Control

There is no guarantee that the next adjustment will be better than the present one. So backup and restore functions must be provided to save the current improved control points using backup control. If the next round of adjustment is not better than the current one, the system can restore the previous set of control points with restore control. In practice, this is a very useful feature for the animator.

DOF and Control Point Selector

Since only one control point of a DOF could be adjusted at a time, two keys are assigned to select the DOF cyclically. One is for up-loop selection while the other is for down-loop selection. Of the continuous controls, the adjusting control point was selected automatically at the current running time. For discrete control, the adjusting control point was selected by the user with left and right keys.

Control Point Adjustor

Different DOF may have different capabilities. This is reflected from the maximal and minimal limits of this DOF. The delta torque of DOF's may also be different. Within the maximal and minimal limits, the animator can intuitively add or subtract a delta torque to this DOF's control point.

What an animator should keep in mind is that, as shown in Figure 6.2, a positive value control point will increase the tendency of this link to swing anti-clockwise; while a negative value control point will increase the swinging tendency in the clockwise

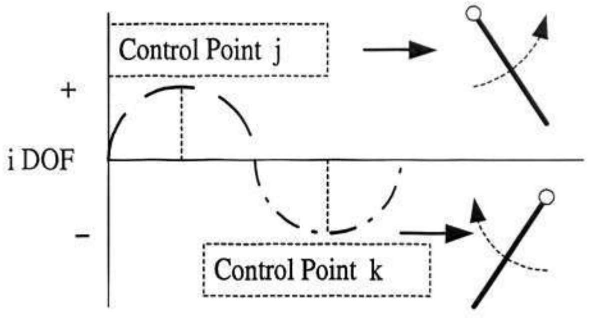


Figure 6.2: Control Point Adjustor: a positive value control point will increase the tendency of this link to swing anti-clockwise; while a negative value control point will increase the tendency to swing clockwise

direction. Any changes to any control points will transfer this DOF's control points to a torque curve generator to regenerate a new torque.

Torque Curve Generator

Any changes in control points will lead the torque curve to be regenerated. In this thesis, a B-Spline was applied as our torque curve generator.

6.3 Interface of Interactive Control

The actual interface of the interactive control contains three parts: the motion observation part, the information displaying part and the torque adjusting part, as shown in Figure 6.3.

The motion observation part is located at the center of screen which is for perceiving the brachiation details. The three yellow color bars present the left hand holding bar, the right hand holding bar and the target bar. The blue color link represents the trunk. The green color and red links represent the lower (arms and legs) and the upper (arms and legs) respectively. The brachiation sequence can be viewed in three dimensions according to keyboard control by the animator. As shown in Figure 6.4, the viewpoint has been changed to front-right-low position. This viewpoint adjusting function is useful to the animator to observe the brachiation.

The information displaying part located at the left-upper part of the screen can be divided in three group from top to bottom: (1) state displaying part provides the information to the animator, such as the present controller, motion phase, kinetic, potential energy, the distance sensor and the minimum distance the brachiator reached. (2) the angular sensors of the brachiator are displayed in this part. (3) the torque curves and control points displaying and adjusting parts. In this part, the torque curves and control points are displayed. The left side larger squares indicate the present adjustable control points. The larger squares on the right side indicate the current running time. key "a" and "z" were set to increase and decrease the current control point respectively. The "[" and "]" keys were set to select control link from RUA to LLL. "<" and ">" are set to slide the controllable squares moving left or right. "-" and "+" are for decreasing the simulation speed.

It should be noted that this simple interface was designed for research and demonstration purposes. Whilst it proved quite usable to demonstrate the controllability of interactive control, the design of the human interface needs more detailed study to improve and optimise the usability.

6.4 Summary

An animator is able to modify the subtle movements by adjusting the torque applied to the joints. This can be achieved by manipulating the control points of a B-spline curve approximating the trajectories of the joint torques. It is anticipated that the joint torque values can be iteratively tuned by studying the visual results generated from the state outputs (i.e. angle, velocity and acceleration) of the dynamics simulation.

This indicates that the controllability of interactive control is very high. Meanwhile automaticity is very low, especially, when the number of DOFs is increased. Individually applying interactive control to animate brachiation would be a tedious task. More versatile control is desirable.

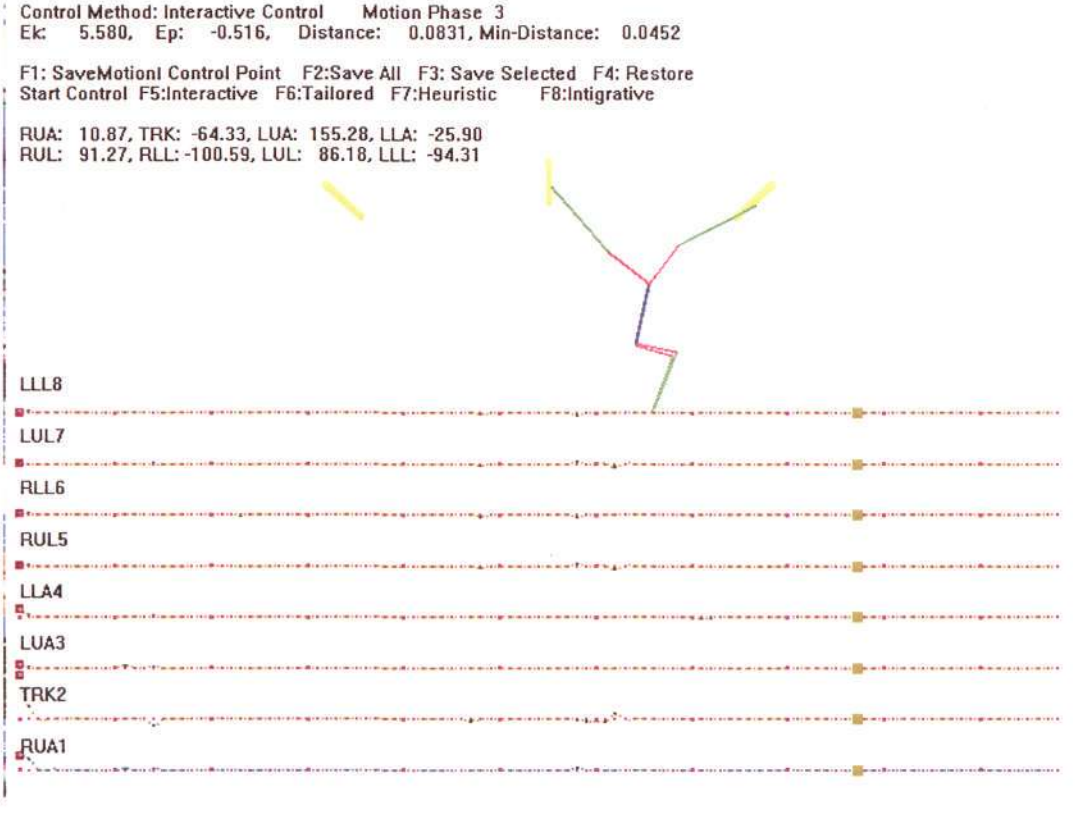


Figure 6.3: The actual interface of interactive control contains three parts: the motion observation part (middle), the information displaying part (top) and the torque adjusting part (lower).

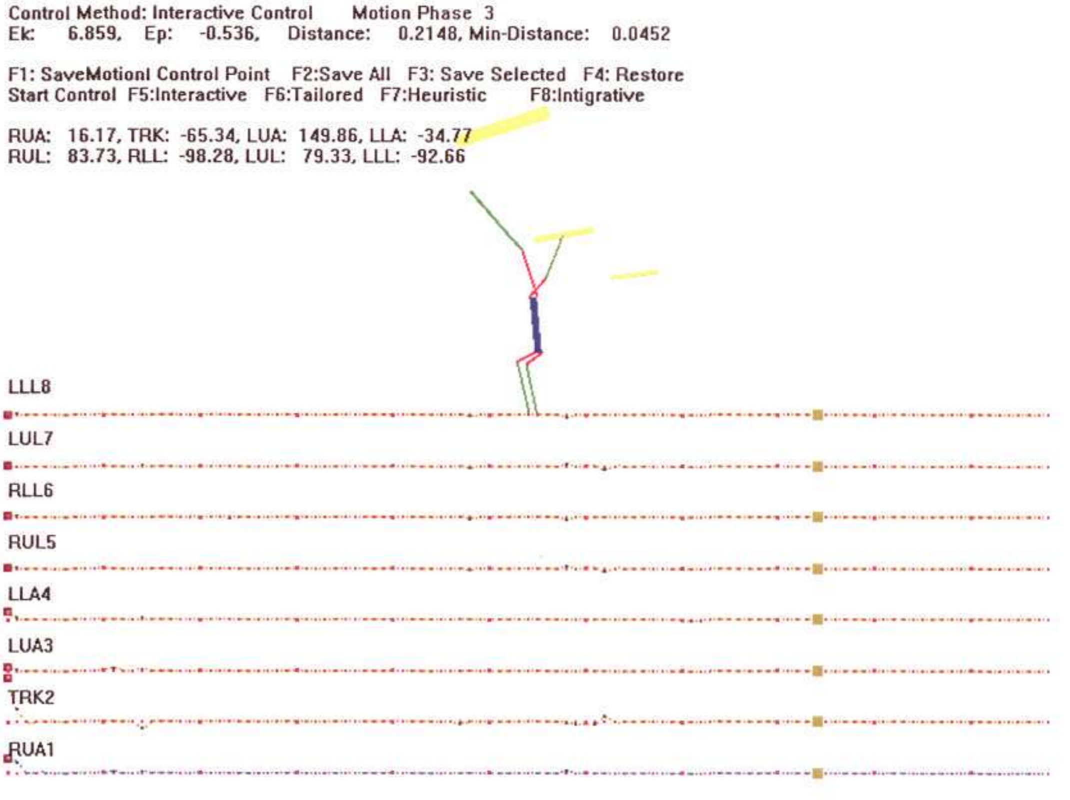


Figure 6.4: The brachiation sequence can be viewed in three dimension according to the keyboard control by the animator. In this figure, the viewpoint has been changed to front-right-lower position.

Chapter 7

Integrative Control

In the previous chapters, tailored control, heuristic control and interactive control for the control of 3-Link and 9-Link brachiation have been described. Each has their own advantages. At the same time, they also have their specific inherent disadvantages. As mentioned before, tailored control and heuristic control possess relatively high automaticity but poor controllability. Interactive control has relative high controllability, but poor automaticity.

In tailored control, after the appropriate motion phases and the desired kinematics data (angles, velocities and accelerations) have been determined, as well as the PD parameters of the control have been set accurately, the system could automatically generate a fantastic brachiation motion sequence. But it is very hard for an animator to generate a different style of brachiation with the same system.

Similar to tailored control, heuristic control maintains higher automaticity after the control algorithm has been developed and the objective functions have been set up. However, it will be more difficult than tailored control to generate different kind of motion sequence, even if there is only a slight difference in motion sequence. Moreover, a natural looking motion sequence can hardly be described in a series of objective functions.

The interactive control provides the animator with a tool to generate various motion sequences. Furthermore, these motion sequences are picked up by the animator as they anticipate and conform to the laws of physics; although, using mathematics and physics, they may be very difficult to describe. The knowledge an animator should know well is that: when increasing the torque, the motion tendency of the related link of that DOF will swing forward; otherwise backward. This demonstrates that the controllability is quite high. However, when the structure of the character is very complex, interactive control may be tedious for adjusting all DOFs and controlling every detail of the whole sequence.

Inspired by the forementioned features of three controls, a novel integrative control method which blends the three levels of control is designed to provide both high controllability and automaticity to animators. To our best knowledge, the concept of integrative control was presented for the first time by the author in 1999 [72, 73]. Below, the necessary technique as implemented in this thesis is introduced. This is followed by an introduction to integrative control. The details of integrative control are presented according to their classification. Finally, a brief summary is presented.

7.1 Technique of Integrative control

Through the previous analysis, we know that blending these three controls is a good idea. But how to implement three distinct controls together is a difficult challenge.

Two basic techniques that utilise two databases, i.e. control point database and kinematics database, have been discovered for integrating. The first technique is control point transfer: the control points generated by the previous control, are stored in the control point database. The subsequent control restores the control points. Based on these control points, the following control starts. Another is kinematic data inheriting: the kinematic data is stored in a kinematic database by the previous control. The following control first inherits the kinematic data, then begins a normal control.

7.2 Category of Integrative Control

There are two different kinds of classification. One is based on the interval while the other is based on the controller. They are introduced below.

7.2.1 Interval

From the viewpoint of interval, there are two different kinds of methods: series integrative control and parallel integrative control, as shown in Fig.7.1. Series integrative control arbitrarily divides the whole animation interval into several parts. To each part, the animator applies different controllers as described below. Parallel integrative control applies different controllers to the same control interval. There are also two sub-methods in parallel integrative control: pseudo-parallel and real-parallel integrative control. Pseudo-parallel integrative control applies one control to an interval after it has finished a different control to this same interval. These two controls are applied to this interval sequentially. Real-parallel integrative control applies two different controls to the same interval simultaneously.

7.2.2 Controller

From the point of view of the controller, there are three kinds of integrative controls: Tailored and Interactive control (TIC), Heuristic and Interactive control (HIC), and Heuristic and Tailored control (HTC). They are introduced below.

7.3 Tailored and Interactive Control

Tailored control and interactive control can be integrated together with series and parallel integrative control.

$$TIC: \begin{cases} Series \begin{cases} ITSC \\ TISC \end{cases} \\ Parallel \begin{cases} Pseudo-TIPP \\ Real-TIRP \end{cases} \end{cases}$$

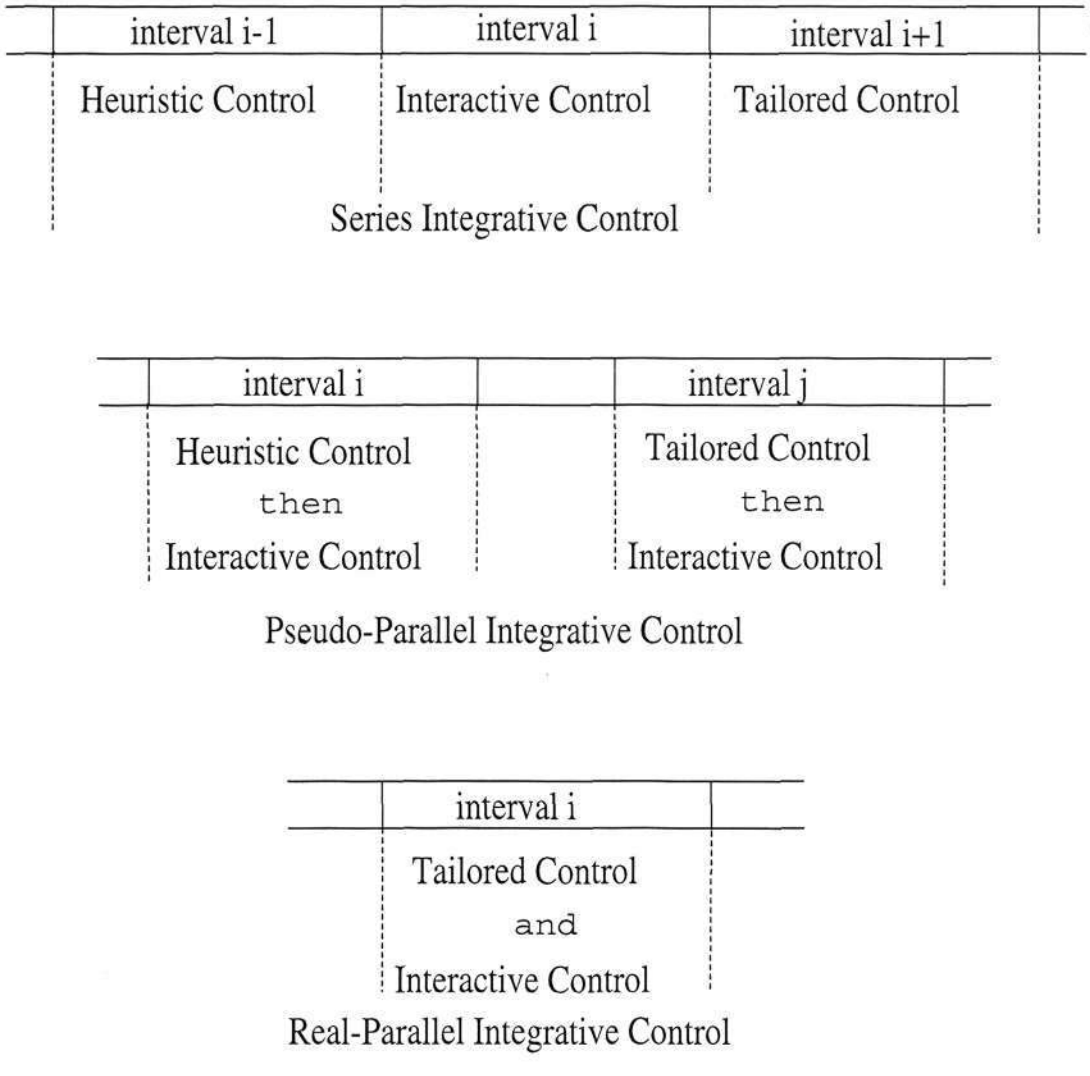


Figure 7.1: Classifying integrative control from control interval.

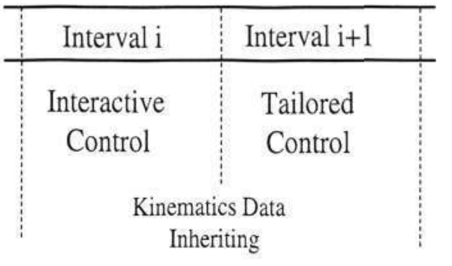


Figure 7.2: Integrating tailored and interactive control applied serially.

When tailored control serially integrates with interactive control, the kinematic data inheritance method is adopted. In the case of tailored control integrating with interactive control, the control point transference method is applied.

In tailored-interactive series control, as shown in Figure 7.2, interactive control not only can be implemented before tailored control, ITSC, but can also be implemented after tailored control (TISC). Both adopt the kinematics data inheritance method for the integration.

In ITSC, interactive control generates a set of kinematic data and passes it to tailored control. The essence of tailored control is Proportional-Derivative control and is based on the kinematic data of the present state. So inheriting the kinematic data will affect the tailored control to generate a satisfactory motion sequence.

In TISC, interactive control succeeds the tailored control by inheriting the kinematic data generated by the tailored method. It will be useful in actual animation production when a certain interval is not easy for interactive control but may be easy for tailored control. We can apply tailored control on this interval then serially integrate interactive control.

In the pseudo-parallel control, TIPP, as shown in Figure 7.3, the tailored method could be applied first on a certain control interval to generate a set of torque curves. These curves are sampled into a set of control points and transferred to interactive control. To the same interval, guided by these control points, the animator could adopt

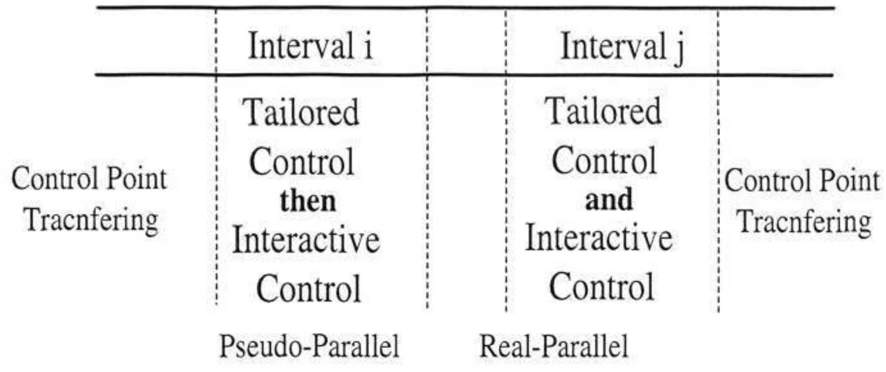


Figure 7.3: Integrating tailored and interactive control in parallel.

interactive control to modify related control points to generate a more satisfactory motion sequence.

In the real-parallel control, TIRP, can handle two cases: one is similar to TISC where the results of tailored control provide a reference to the following interactive control. But the reference is provided in real-time rather than off-line as in TISC. Another case, when applying interactive control to adjust the control points of one DOF, others DOFs can apply tailored control simultaneously. This should significantly reduce the work load of the animator, especially when the system has many DOFs.

7.4 Heuristic and Interactive Control

When interactive control is integrated with heuristic control, HIC, series and pseudo-parallel methods are able to be applied using kinematic data inheritance and control point transferring techniques respectively, as shown in Figure 7.4.

$$HIC : \begin{cases} Series \begin{cases} IHSC \\ HISC \end{cases} \\ Pseudo - Parallel\ Control\ HIPP \end{cases}$$

However, real-parallel integrative control is not available. These are detailed below.

In heuristic-interactive series control, interactive control can be implemented before heuristic control, IHSC. It can be implemented after heuristic control as well,

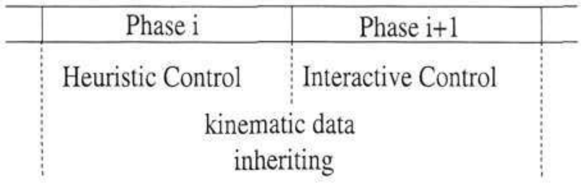


Figure 7.4: Serially integrates interactive control with heuristic control.

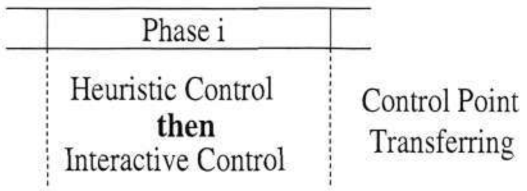


Figure 7.5: Heuristic Interactive pseudo-parallel Control, HIPC

HISC. But the significance is a little different. Both of them adopt the inheritance kinematic data method to integrate. The previous control produces the angles, velocities and accelerations and transfers them to the following one.

When heuristic control integrates interactive control in parallel, only pseudo-parallel is appropriate. The real-parallel method is not available, because heuristic control is a closed-loop process. If the real-parallel method is applied, the heuristic algorithm may be disturbed by the adjustment of interactive control. Finally, no sequence will be obtained.

In the pseudo-parallel control, as shown in Fig. 7.5, the heuristic method could be applied first so that we can get a set of torque control points. These control points are transferred to interactive control as reference points. Under the guidance of these control points, the animator could adopt interactive control to modify related control points to generate a more satisfactory motion sequence. On one hand, the controllability of heuristic control has been improved. There are a variety of "deformation" motion sequences based on the one generated by heuristic control. On the other hand, the guidance provided by heuristic control reduces the tedious work of interactive control so that automaticity has been improved simultaneously.

IHPC does not appear to be a good approach. This is because after the control points have been obtained by applying interactive control, and adopting heuristic control in parallel to the same control interval will omit them and could not help in controlling the motion.

7.5 Heuristic and Tailored Control

The parallel control is not suitable for integrating heuristic control with tailored control. Only series control method is appropriate, HTSC or THSC.

$$HTC : Series\ Control \begin{cases} HTSC \\ THSC \end{cases}$$

Which control to apply first depends on to the actual situation.

Heuristic control can be integrated with tailored control. However, considering the goal is to improve controllability and automaticity, HTC is not a good choice because both of them have quite high automaticity but lack controllability.

7.6 Summary

In this chapter, a novel method for integrating interactive, tailored and heuristic control has been introduced, as shown in Table 7.1. The necessary condition for integrative control is discovered based on control points and kinematics data. The category of integrative control is presented and related methods are detailed according to different categories.

This integrative control is valuable to animate brachiation. For instance, if a certain interval is difficult for interactive control, then high automaticity tailored control or heuristic control can be applied first to generate the appropriate torques. Identifying the unsatisfactory interval (if any), and applying interactive control on it would help solve the problem. Even when we are applying interactive control, the tailored control not only can be applied in an off-line series manner, but also in a real-time parallel manner, i.e., it is also able to be adopted in the real-parallel style to generate a set of reference torques for interactive control. Dynamically and appropriately applying integrative control which integrates interactive control with heuristic and tailored controls is a sophisticated and versatile solution to animation of brachiation.

Serial Integrating	Tailored control	Heuristic control	Interactive control
Tailored control	Nothing integrated TTSC	Lacks controllability HTSC	High automaticity and controllability ITSC
Heuristic control	Lacks controllability THSC	Nothing integrated HHSC	High automaticity and controllability IHSC
Interactive control	High automaticity and controllability TISC	High automaticity and controllability HISC	Nothing integrated IISC
Pseudo Parallel	Tailored control	Heuristic control	Interactive control
Tailored control	Nothing integrated TTPP	Not Applicable HTPP	Destroyed controllability ITPP
Heuristic control	Not Applicable THPP	Nothing integrated HHPP	Destroyed controllability IHPP
Interactive control	High automaticity and controllability TIPP	High automaticity and controllability HIPP	Nothing integrated IIPP
Real Parallel	Tailored control	Heuristic control	Interactive control
Tailored control	Nothing integrated TTRP	Not Applicable HTRP	Not Applicable ITRP
Heuristic control	Not Applicable THRP	Nothing integrated HHRP	Not Applicable IHRP
Interactive control	High automaticity and controllability TIRP	Not Applicable HIRP	Nothing integrated IIRP

Table 7.1: The categories of integrative control.

Chapter 8

Experimental Results

In this chapter, the results of a representative experiment are described to exemplify the effectiveness, robustness and problems of the proposed brachiation control paradigms described in the previous chapters.

The equipment used to implement the 3-Link brachiation animation system was an SGI workstation using the Unix operating system, while the 9-Link brachiation animation system was implemented on a personal computer using the Windows operating system. Both systems used the OpenGL graphics library to display animation sequences on the screen. The motion sequences illustrated in the following sections are generated using the 3-Link or 9-Link brachiation animation system and captured with SnagIt software.

In the experiment, the analysis of three parameters are summarized, the kinetic energy (E_k), potential energy (E_p, we set the level of the holding bar as the zero level of potential energy), the distance between the palm of a grasping hand and a target (D) and the realism of an animated sequence. The first three metrics, E_K, E_P and D, are employed to quantitatively measure the performance of the controllers for swing down, swing up and grasping actions, respectively. To assess the realism of brachiating motion, this can only be achieved qualitatively.

As space is limited, only typical experimental results are reported here based on the two different complexity models: the 3-Link and the 9-Link models. To illustrate the animation a cd containing the experimental results of the free-swing, tailored control, heuristic control, interactive control and integrative control, is attached with this thesis. In this chapter, we start from the free swing motion where, excluding gravity, there is no other force or torque to propel the swing movement. The free swing results are the basic benchmarks for the experiments described in the following sections, using tailored control, heuristic control, interactive control and integrative control. After reporting the results of these controls, a brief summary is presented at the end of each section.

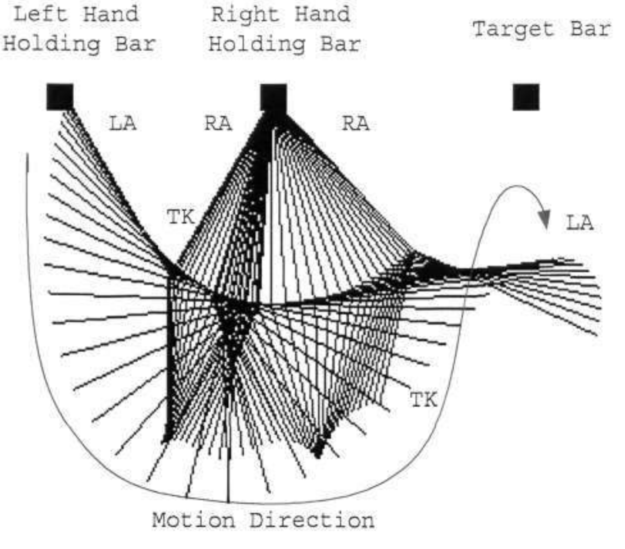
8.1 Results of Free Swing

The initial state of free swing is that the brachiator grasps two holding bars with the right and left hands respectively. While the brachiator begins to brachiate, it releases the left hand and swings forward freely with the right hand keeping holding the bar. Except for gravity and the holding force between the right hand and the holding bar, there is no other torque or force acting on any links or joints of the brachiatior to pump energy into the system. The experimental results are reported below according to the different models.

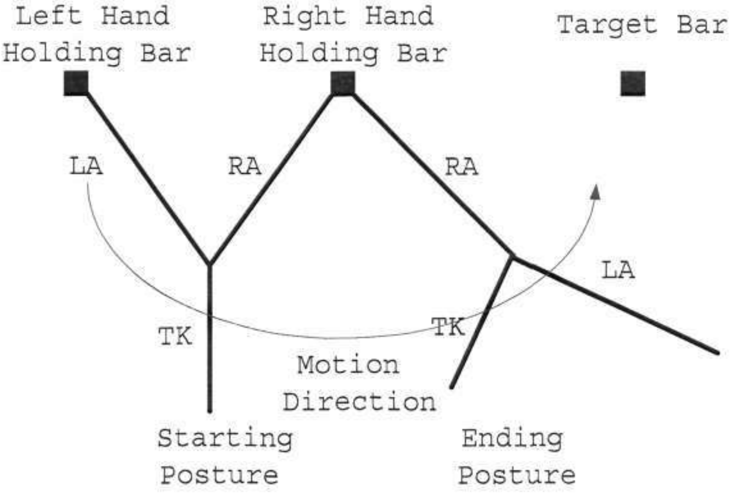
3-Link Free Swing

It is obvious, as shown in Figure 8.1, the brachiator cannot catch the target bar without active force or torque pumping energy into the system.

As shown in Figure 8.2, the initial potential energy at the HLD phase is -0.78. The greater potential energy value indicates that a higher level swinging motion can be reached. During the swing motion the highest potential energy is -0.89, this value is even less than the initial value. This indicates that without control, and influenced only by the effect of gravity, the 3-Link brachiator swings lower than the initial phase and fails to catch the target bar.

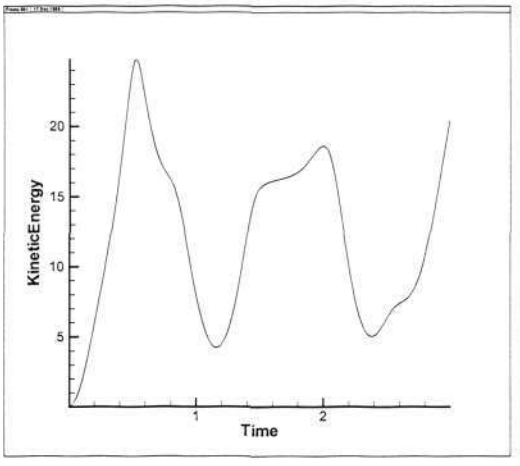


(a) All in One

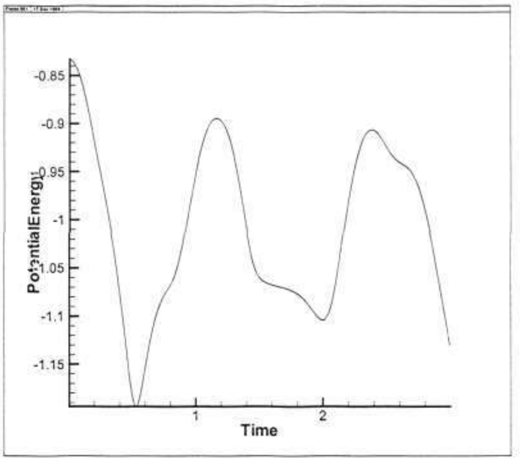


(b) Start and Ending Posture

Figure 8.1: (a) 3-Link Free Swing. The brachiator cannot catch the target bar without active force or torque pumping energy into the system. The green line indicates the brachiating direction. (b) The starting posture and the ending posture of the brachiator. The 3-Link model is as shown in Figure 3.4.



(a) Kinetic energy



(b) Potential energy

Figure 8.2: Kinetic Energy and Potential Energy of 3-Link Free Swing

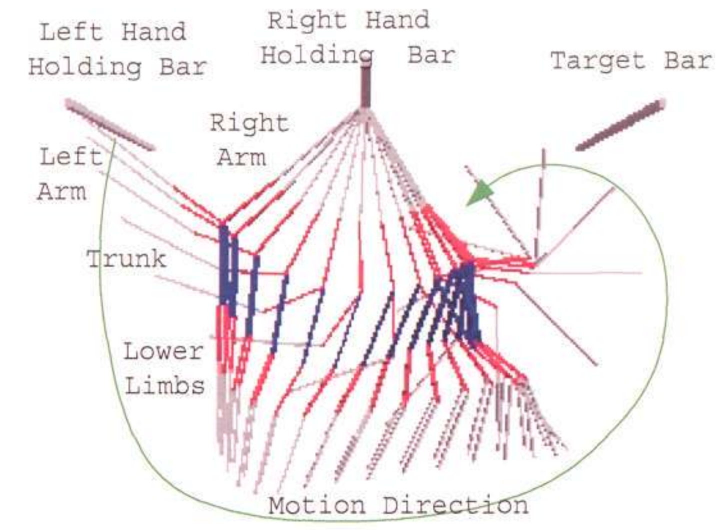
9-Link Free Swing

The starting condition of the 9-Link free swing is that the brachiator holds the holding bars with both left and right hand. After the brachiator releases the left hand to swing, apart from gravity, there is no torque or force acting on the links or joints. The experimental result shows that the brachiator cannot catch the target bar, as shown as Figure 8.3.

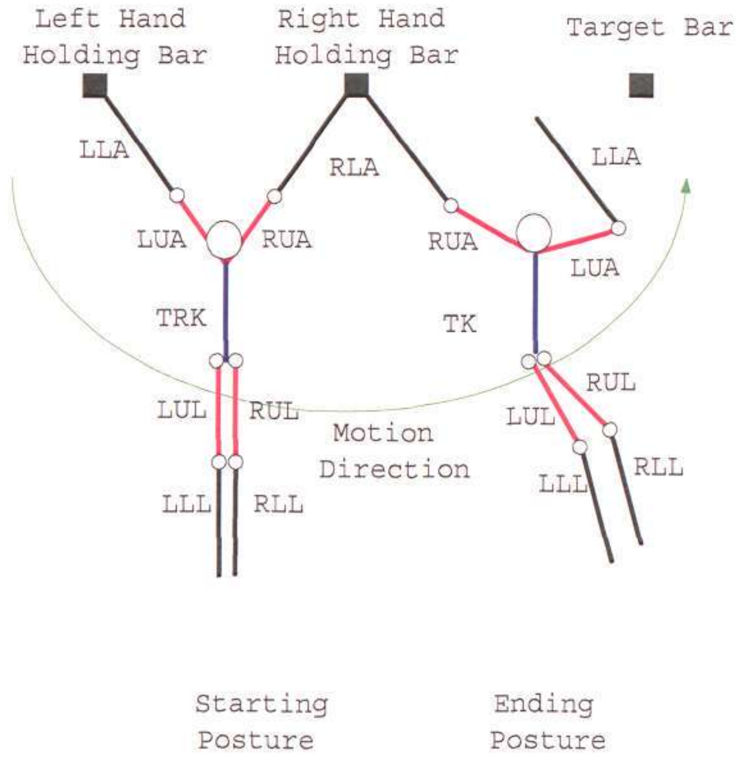
The nearest distance that the brachiator can reach the target is $0.26m$ at the time 0.925 second as shown in Figure 8.4. The maximum kinetic energy it can reach is 19.60 at 0.52 second and at the same time, it obtains the minimum potential energy of -0.80. The maximum potential energy it reaches is -0.63 at the time 0.995 second. It is less than the starting potential energy of -0.49, so we can observe that the motion is weak.

Summary of Free Swing

Except for gravity, if there is no other torque or force exerting to help the swinging up motion, the brachiator cannot catch the target bar. This is different from a single link pendulum where the pendulum can at least swing as high as the initial state at the end of the SFU phase. The reason why the 3-Link and 9-Link models are unable

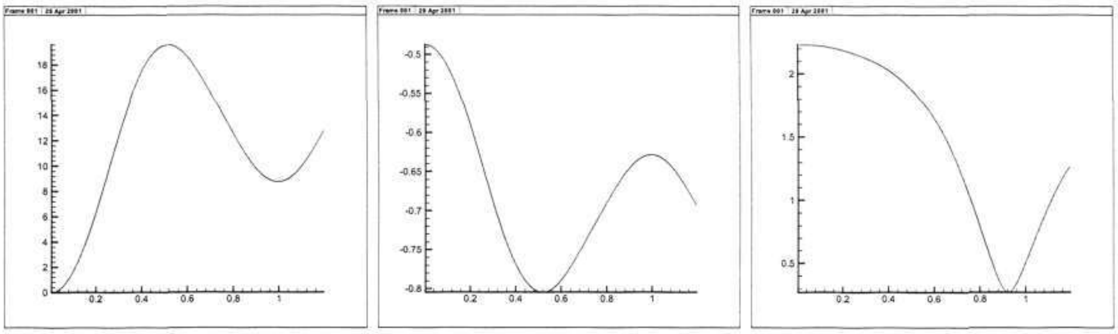


(a) Motion All in One.



(b) Start and Ending Posture

Figure 8.3: 9-Link Free Swing. The experimental result shows that the brachiator cannot catch the target bar. (b) The starting posture and the ending posture of the brachiator. The green line indicates the brachiating direction. The 9-Link model is as shown in Figure 3.5.



(a) Kinetic Energy (b) Potential Energy (c) Distance to Target

Figure 8.4: Kinetic Energy, Potential Energy and Minimum Distance of a 9-Link Free Swing (energy and distance vs time).

to swing up like a single pendulum is the complexity of the model. As the number of links in the brachiator model increases, the interference between the links during the swinging motion becomes serious. For example, in a multiple links system, when one link is swinging forward, meanwhile, another link may finish swinging forwards and start to swing backwards, causing the swinging forward tendency of the first link to be curtailed by the motion of the link which is swinging backwards.

From the previous analysis, we realise that without proper control to pump energy into the system with appropriate force or torque, the brachiator is unable to swing up and grasp the target bar.

8.2 Results of Tailored Control

In this section, the experimental results of tailored control that possesses high automaticity and low controllability are reported based on the 3-Link and 9-Link models. At the end of this section, a summary is given.

8.2.1 3-Link Tailored Control

In the SFD phase, the lowest potential energy the brachiator reaches is -1.1, as shown in Figure 8.6 (b). At the end of SFD, the posture of the brachiator does not extend straight as required. In the SFU and GRP phases, the brachiator is able to grasp

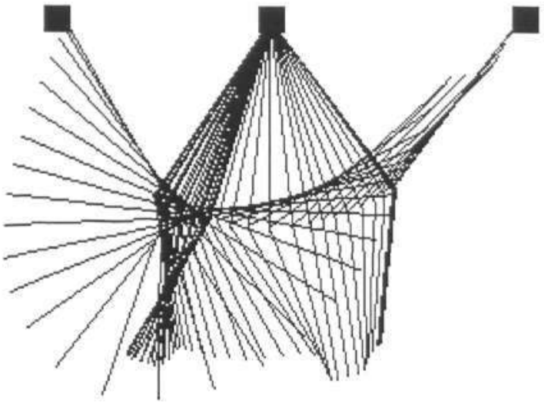
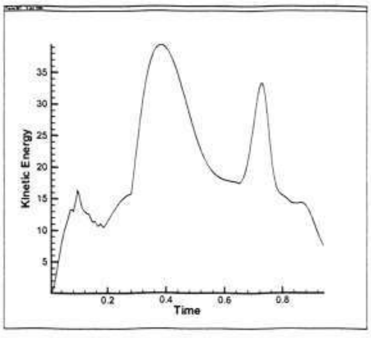
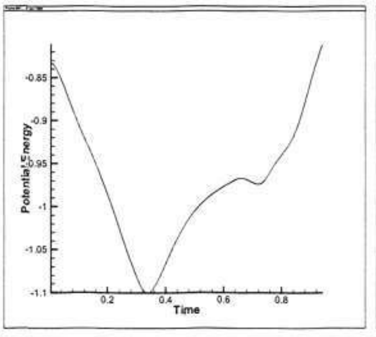


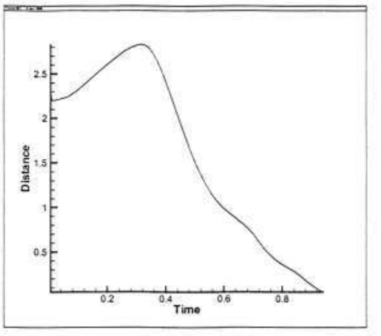
Figure 8.5: 3-Link Tailored Control Results



(a) Kinetic Energy



(b) Potential Energy



(c) Distance

Figure 8.6: Kinetic Energy, Potential Energy and Minimum Distance of 3-Link tailored control.

the target bar with the trunk almost perpendicular with the ground as expected, and as shown in Figure 8.5. Meanwhile, the highest potential energy is -0.81 which is higher than the starting potential energy, -0.83. It is also greater than the potential energy that the brachiator obtained in free swing, -0.89. It indicates that the tailored control successfully pumps sufficient energy into the system and controls the posture properly so that the brachiator could catch the target bar with a satisfying posture.

8.2.2 9-Link Tailored Control

After we apply the 9-Link tailored control module, a successful Swing-Forward-Once-Grasp (SFOG) motion sequence is obtained, as showed in Figure 8.7. Although at the end of the SFD phase, the gesture is not extending straight, the motion postures are excellent and achieves the requirements in the GRP phase. For instance, in the GRP phase, the trunk is almost perpendicular with the ground and the angles between the trunk and the upper legs, and the angles between the upper legs and the lower legs are almost 90 degree as we specified in the requirement.

The related motion data shown in Figure 8.8 also demonstrates that the control results are efficient. It could also be quantitatively discovered from the potential energy value. At the end of the GRP phase, the potential energy that reaches -0.53 under tailored control, as shown in Figure 8.8 (b), is greater than the free swing motion's value of -0.63. It indicates that tailored control is able to effectively pump energy into the system to swing up.

The greatest kinetic energy that the brachiator achieved is more than 28.0 during the GRP phase, as shown in Figure 8.8 (a), and is greater than the 19.6 that the brachiator obtained in free swing motion. The greater kinetic energy value shows that to achieve our posture requirement and successfully catch the target in the GRP phase, tailored control has controlled the related links effectively.

8.2.3 9-Link Holding Arm Control

In this experiment, we applied the holding arm control before the general 9-Link tailored control. As shown in Figure 8.9 (a), the brachiator pulls the COM up-backward by flexing up the left arm; swinging the trunk backward; and drawing up the lower limbs. After it has achieved holding arm control, as shown in Figure 8.9 (b), the brachiator starts a general swing-forward-once-grasp (SFOG) motion, and catches

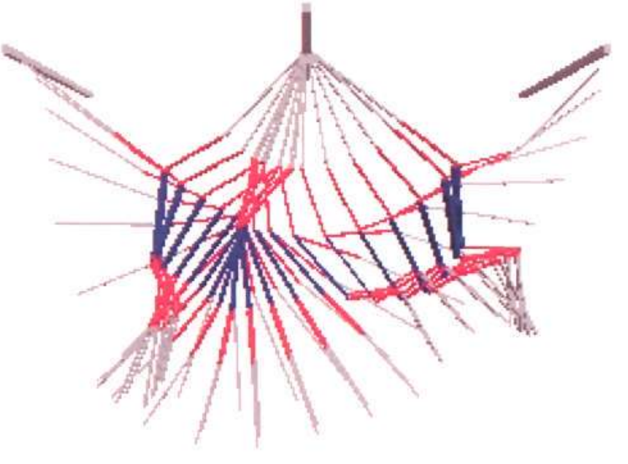
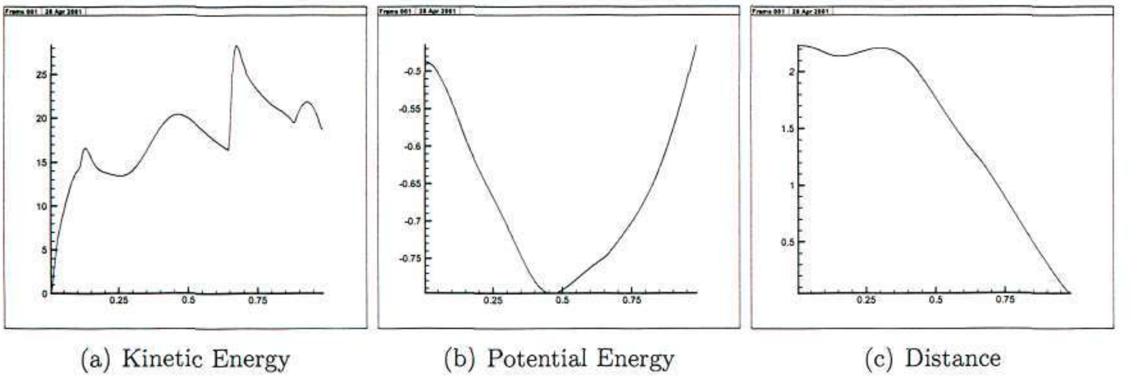


Figure 8.7: 9-Link Tailored Control Results



(a) Kinetic Energy (b) Potential Energy (c) Distance

Figure 8.8: Kinetic Potential Energy and Distance Data of Tailored Control.

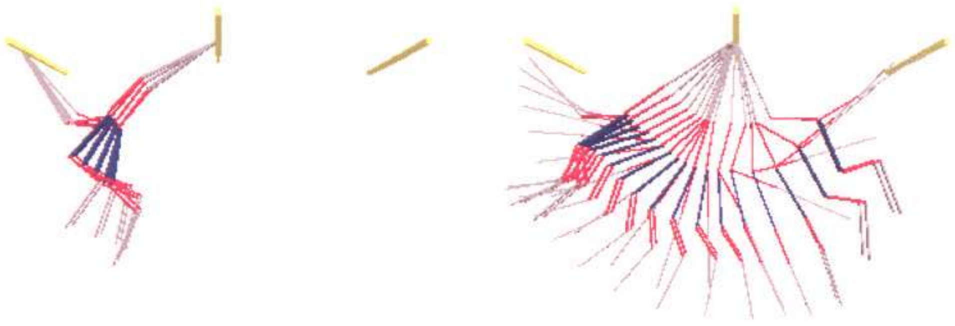
the target bar. Except for the trunk swinging a little bit forward at the GRP phase, the movement is satisfying and realistic.

Comparing this with the results of general tailored control without holding arm control, the brachiator can more easily pump energy into the system through holding arm control before the brachiator releases the holding arm to start a general brachiation motion. That is why we can observe that the SFOG motion after holding arm control, shown in Figure 8.9 (b), is more powerful than the normal SFOG with general tailored control.

The same result can be obtained through analyzing the measurement data shown in Figure 8.10. The potential energy reaches the highest level of -0.41 at 0.365 second. It is greater than that achieved in general tailored control, shown in Figure 8.8, when the brachiator directly releases the holding bar, the potential energy reaches -0.45 at the starting time.

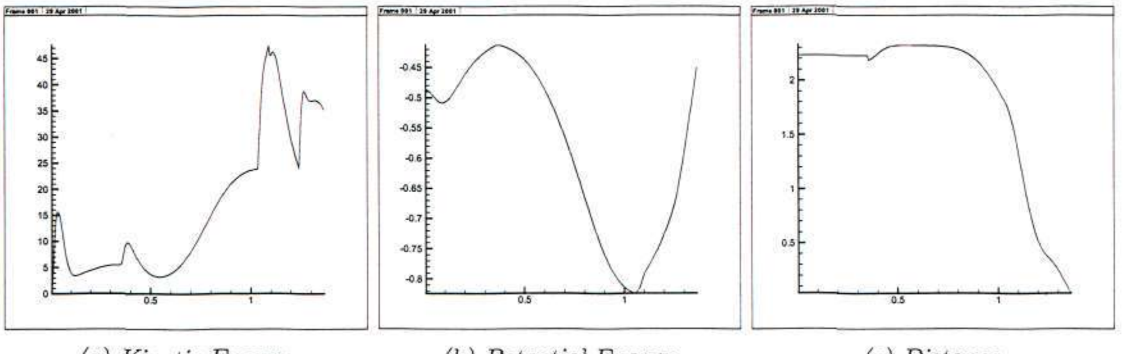
Comparing the potential energy curves between the holding-arm-control, in Figure 8.10 (b), and the general tailored control, in Figure 8.8 (b), there is an interesting difference. In general tailored control, from the beginning, the curve turns directly down during the SFD phase. Meanwhile, in holding arm control, after the curve turns down within 0.1 seconds, it amazingly turns upward till 0.365 seconds and reaches a maximum value of -0.41. The first turning down caused by the holding arm control starts to adjust the posture by curling the left arm suddenly, and the trunk is forced to swing forward and the COM falls down. After the holding arm control handles the situation, the COM is effectively pulled up. That is why we can observe that the curve turns upward from 0.1 to 0.365 seconds.

The analysis indicates that the hold arm control is able to improve brachiation. Figure 8.9 (a) shows the holding arm adjusting phase, and Figure 8.9 (b) shows the general SFOG brachiation motion.



(a) Hold-Arm-Control (b) General-SFOG

Figure 8.9: (a) Holding arm control phase; (b) General swing-forward-once-grasp phase



(a) Kinetic Energy (b) Potential Energy (c) Distance

Figure 8.10: Energy and distance of holding arm control.

8.2.4 Summary of Tailored Control

The parameters of tailored control were hand-tuned with a hundred trial and error experiments. They are adequate for the control rather than globally optimal parameters. Through experiments, we can confirm that after hand-tuning the parameters tailored control is able to control swinging up effectively, as well as precisely grasping the target. Adopting the holding arm control could improve the effectiveness of swinging up, and the brachiation motion is more powerful.

From the viewpoint of automaticity and controllability, after completing the design of the tailored control for brachiation, a final user just needs to run this software. The related kinematics data would be obtained and the relative motion sequences would be displayed on the screen or saved into hard disk for later usage. We can conclude that the automaticity of this tailored control is quite high compared to the key-frame kinematics method where the user needs to interactively adjust a series of so-called key frames to generate a final motion sequence.

On the other hand, we also realize that it is not easy for a user to generate a new series of brachiation motion sequences based on the existing tailored control. For instance, in the experimental result for the 9-Link model, a final user, an animator, would be facing the same problem when his movie director desires another kind of emotional brachiation. He may need another set of motion sequences where the trunk needs to not be perpendicular with the ground in the GRP phase. Unfortunately, the animator can do nothing any more. From this point, we must conclude that the controllability of tailored is not satisfied.

8.3 Results of Heuristic Control

To evaluate heuristic control, many experiments were performed based on the 3-Link and 9-Link models. As space is limited, this report focusses on the typical results in the following sections. The experimental results of 9-Link heuristic control can be found in the CD attached with this thesis. At the end of this section a brief summary is presented.

8.3.1 3-Link Heuristic Control

3-Link and 9-Link phase heuristic control each apply different objective functions to different motion phases. The 9-Link phased-heuristic-control (PHC) is presented in section 8.3.2. The experiments were designed as follows. First, all the control points were set to zero, and start to control the SFD phase. The control points generated from SFD were transferred to start SFU heuristic control. Finally, the control points of SFD and SFU were transferred to the GRP phase. Based on the control points of SFD and SFU, heuristic control would be able to determine the control points for the GRP phase. Therefore, the control points for SFOG were obtained and the related brachiation movement could be animated from the torque sequence generated from the control points.

The eventual results generated by the 3-Link heuristic control are shown in Figure 8.11. The 3-Link brachiator is able to catch the target bar through SFD, SFU and GRP phases, although the trunk is not exactly perpendicular to the ground when the brachiator is grasping the target bar in the GRP phase.

The related data are shown in Figure 8.12. The greatest kinetic and potential energy obtained by 3-Link heuristic control are 27.9 and -0.71, and are also greater than the 24.7 and -0.89 respectively obtained in Free Swing motion, as shown in Figure 8.2. This indicates that extra-energy has been effectively pumped into the system using 3-Link heuristic control, so that the brachiator could catch the target.

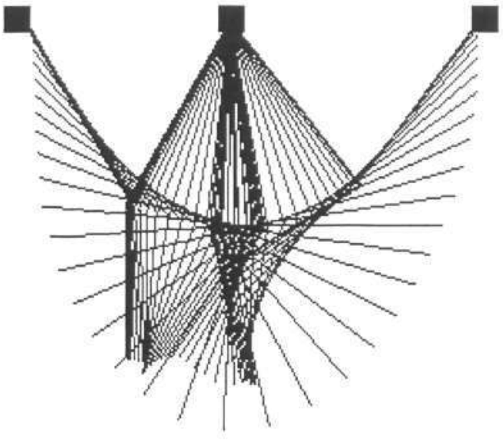
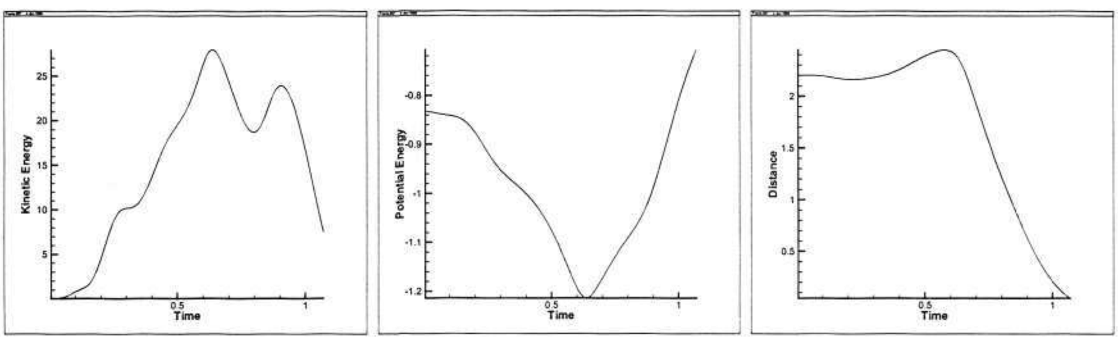


Figure 8.11: 3-Link Heuristic Control Results



(a) Kinetic Energy (b) Potential Energy (c) Distance

Figure 8.12: Kinetic Energy, Potential Energy and Min-Distance of 3-Link Heuristic Control.

8.3.2 9-Link Heuristic Control

Three methods for 9-Link heuristic control (HC) were designed, phase heuristic control (PHC), Final-target heuristic control (FHC) and Phase-Final-target heuristic control (PFHC). In this section, the results of the three HCs are reported and evaluated in the following sections through experiments.

Phase Heuristic Control (PHC)

PHC is based on the phase to phase control, similar to 3-Link heuristic control, which means PHC would start heuristic control from SFD to SFU and GRP phases. The control points obtained from the prior phase are transferred to the following phase, i.e., from SFD phase to SFU phase, and finally to the GRP phase. The motion sequences generated by the current phase control are based on the prior phases (except for the SFD phase).

Although we have tried various parameters of grasping and posture, the grasping motion finally fails. The best result where the brachiator almost reaches the target is shown in Figure 8.13, where the nearest distance between the grasping hand and the target bar is greater than 0.04 metres. Meanwhile, the grasping posture is also not satisfying.

As shown in Figure 8.14, the highest kinetic energy obtained at the end of the SFD phase is 20.0, while, the potential energy reaches -0.77. This indicates that the energy pumped into system is very low. Hence the brachiator has to increase the related joint's torque to perform the grasping motion with a proper posture at the SFU and GRP phases. This exertion causes the violation of fluid motion as, for instance, is observed in the strange motion of the grasping arm shown in Figure 8.13 in the SFU and GRP phases. It is also expressed in Figure 8.14, at the time 0.95 second, the kinetic energy suddenly increases from 20 to 70.

The reason is that the objective function of SFD is not correct for a multi-links

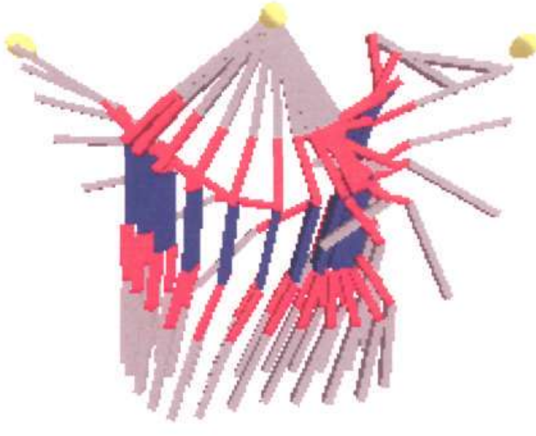
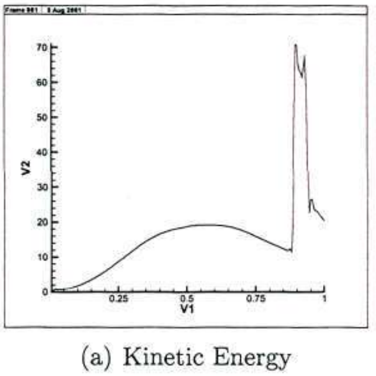
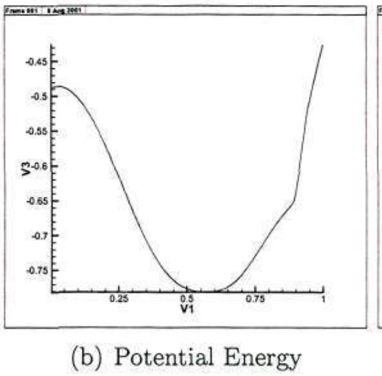


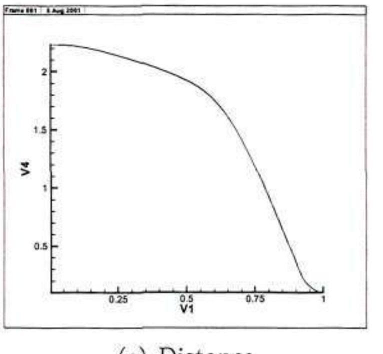
Figure 8.13: Results of PHC control



(a) Kinetic Energy



(b) Potential Energy



(c) Distance

Figure 8.14: Kinetic Energy, Potential Energy and Minimum Distance of the 9-Link Phase-HC.

system, although the same idea is successful in the 3-Link model. There are two terms in the function, posture and kinetic energy. The strategy of the objective function is that less error between the desired pose and currently reached pose is better and more kinetic energy is better. From here we can conclude that the objective function is encouraging exertion in the brachiator to bring more kinetic energy into the system. But more kinetic energy may not always help the motion of swinging-up in a multi-links system. Because the kinetic energy is the sum of all link's kinetic energy according to the laws of physics, increasing a certain link motion, i.e. increasing it's kinetic energy, is not guaranteed to improve the swinging forward-up motion.

For instance, quickly swinging the left-lower-arm (LLA) in a 9-Link system would benefit the system by increasing the kinetic energy in the SFD phase, but it would not be helpful for swinging the whole body forward in an appropriate manner. It is not so serious in the case of the 3-Link model, because encouraging the kinetic energy to increase through swinging the left-arm (LA) or trunk (TK) in a forward direction would benefit the COM to swing forward, which means it would directly help the whole body swinging up in the following SFU phase. However, it is unsuitable for the 9-Link system. More sophisticated heuristic control methods for a 9-Link model are required.

Final-target Heuristic Control (FHC)

Unlike PHC, which applies different objective functions to different phases and starts heuristic control one-by-one from SFD to SFU and GRP phases, final-target heuristic control (FHC) adjusts the entire control points from the beginning to the end of the motion, including SFD, SFU and GRP phases, and applies only one eventual objective function of the GRP phase to measure brachiation. This, it was hoped, would help resolve the drawbacks of PHC.

As shown in Figure 8.15, the 9-Link brachiator can successfully catch the target

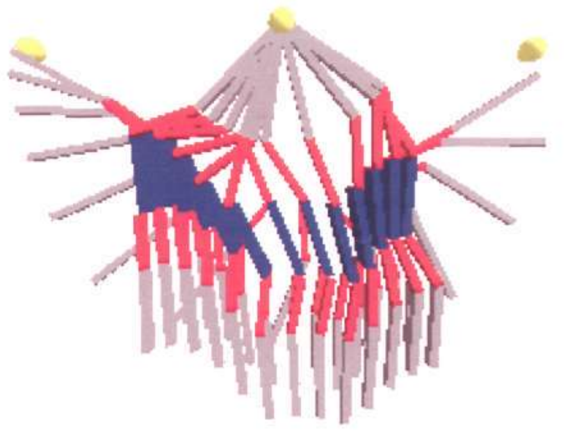
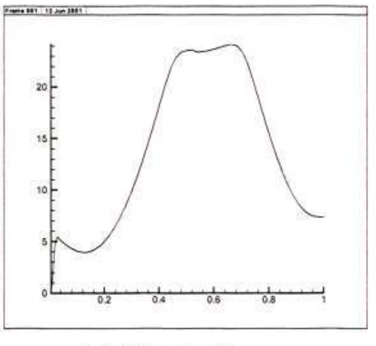
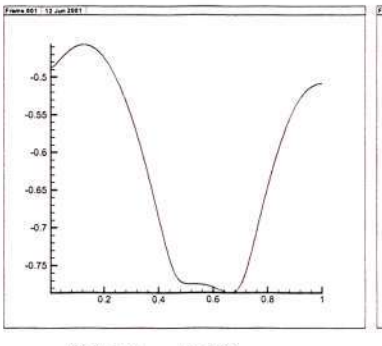


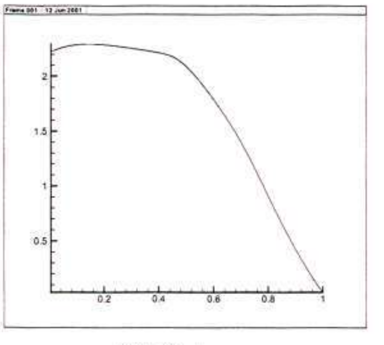
Figure 8.15: 9-Links FHC Results.



(a) Kinetic Energy



(b) Potential Energy



(c) Distance

Figure 8.16: Kinetic Energy, Potential Energy and Min-Distance of the 9-Link FHC.

bar. The minimum distance between the palm and target is 0.03 metres, as shown in Figure 8.16 (c). At the end of the SFD phase, the highest kinetic energy reaches 24 at the time 0.65 seconds, and the greatest potential energy reaches −0.51, as shown in Figure 8.16. The posture of GRP is better than in PHC, but it is not satisfying in the SFD phase.

FHC directly evaluates the adjustment of each control point by measuring the eventual result, i.e. whether it reaches the target or not, rather than according to different objective functions for each phase in PHC. It effectively overcomes the difficulties of evaluating the swinging efficiency of the SFD and SFU phases. There is an interesting and amazing phenomenon in FHC. Let us take a look at Figure 8.16 (b). During the first 0.12 seconds, the COM was being pulled up by heuristic control, although an objective function was not set to guide the brachiator pulling the COM up to benefit further swinging motion. The brachiator has automatically learned to do it in this way. The same situation has been realized in the tailored control as we added the holding-arm-control into the system control, as shown in Figure 8.10 (b).

There is still an existing disadvantage in that we cannot control intermediate postures like the postures of the SFD or SFU phases directly. As indicated in the FHC results section, the posture of SFD is not satisfactory.

Phase-final-target Heuristic Control (PFHC)

Phase-final-target-based heuristic control (PFHC) is different from PHC and FHC. On one hand, it synthesizes the advantages of PHC that considers the posture of every phase. On the other hand, it utilizes the advantages of FHC that evaluates the final grasping effect of brachiation. Below, the parameters of FPHC are first introduced, after which, the experimental results of the three phases, SFD, SFU and GRP, are presented.

Results and Analysis of SFD

As shown in Figure 8.17, the motion posture of SFD is improved compared with the SFD motion of FHC. The trunk and the lower limbs of the brachiator are almost perpendicular to the ground. However, the postures of the SFU and GRP phases are not satisfying in that the lower limbs are not swinging forward as we expect. This may not be a serious problem in the SFD phase control, because we are focusing on the motion of SFD, rather than the posture of SFU and GRP.

As shown in Figure 8.18. At the end of the SFD phase, the highest kinetic energy reaches 24, and the potential energy reaches -0.83. The amazing situation occurred in FHC that increases the potential energy at the beginning of the brachiation can also

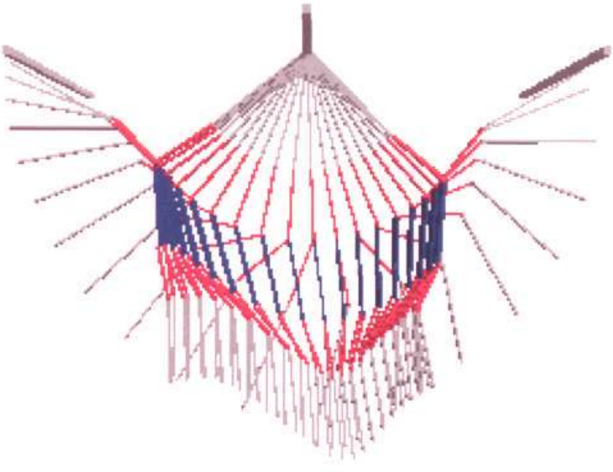
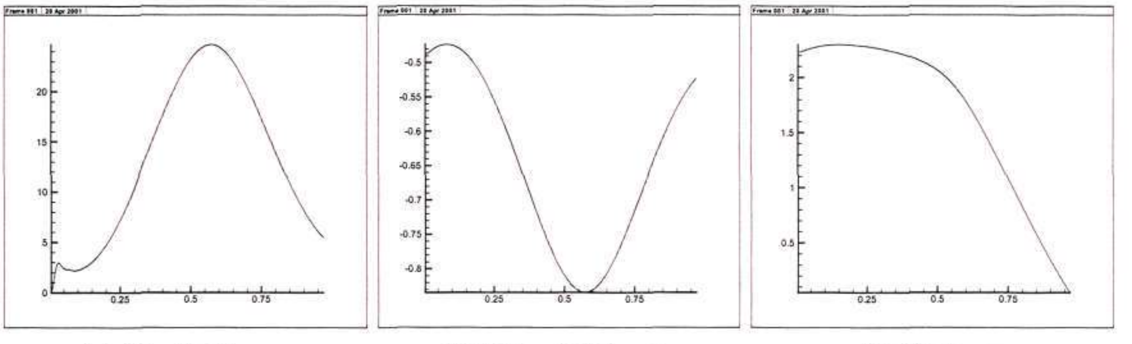


Figure 8.17: SFD Motion Results of 9-Link FPHC.



(a) Kinetic Energy (b) Potential Energy (c) Distance

Figure 8.18: The Kinetic Energy, Potential Energy and Distance of 9-Link FPHC SFD Phase Control

be observed in Figure 8.18 (b). Although the highest potential energy of value, -0.47, that the brachiator reached at the beginning of PFHC is less than -0.46 reached by the FHC, because the PFHC needs to consider the posture, it still indicates that the sophisticated advantage of FHC to control the system by pulling the COM before it swings down is inherited by PFHC from FHC.

Through designing the SFD objective function in using PFHC, we could avoid the complexity of assessing the effect of SFD from the viewpoint of energy in PHC.

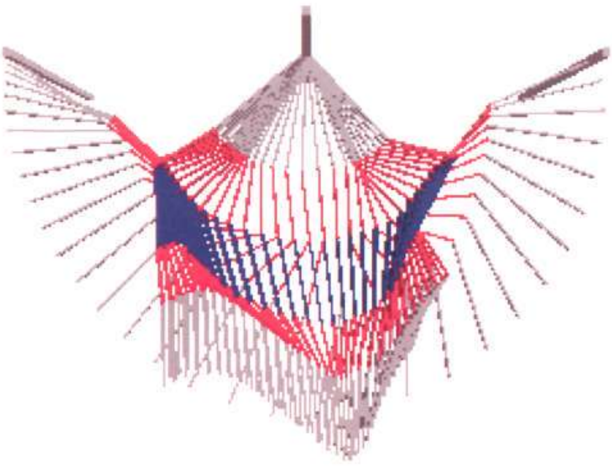


Figure 8.19: SFU Motion Results of 9-Link FPHC.

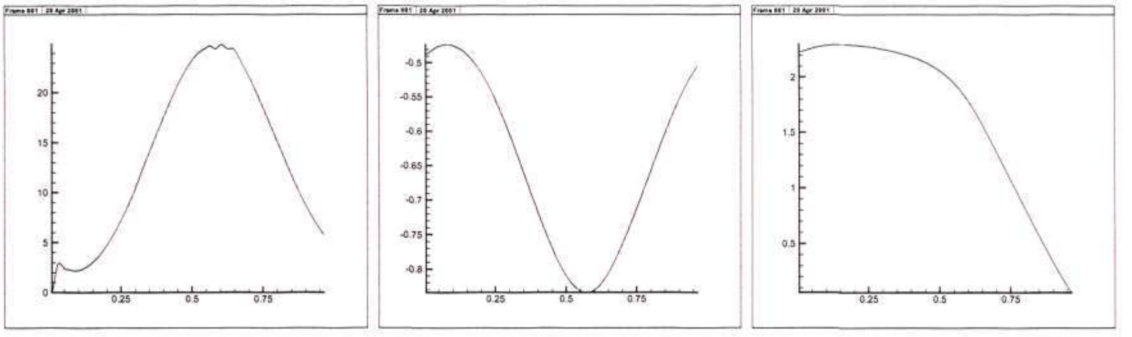
Results and Analysis of SFU

In this phase, the objective function calculates the posture parameter of SFU and the grasping result of GRP. The final results are shown in Figure 8.19. When compared with the results of SFD with FPHC, the posture of the SFU phase is improved. For instance, in the result of the SFD phase, the lower limbs do not swing enough, however in the SFU phase, the angles of the upper legs are almost 45 degree and the angles of the lower legs are almost -45 degree, just as required by the FPHC control.

As shown in Figure 8.20(c), the least distance between the grasping hand and the target is less than 0.04 metres, and indicates that the brachiator successfully caught the target. Because the final posture of GRP is not considered, it can be observed that the gesture of GRP, especially to TRK, is not satisfying.

Results and Analysis of GRP

The control points generated from the previous experiments of SFD and SFU phases of FPHC are transferred to the GRP phase. Based on the control points, GRP FPHC starts heuristic control. It considers the posture of GRP and the distance between the palm of the grasping hand and the target as the two terms of the objective



(a) Kinetic Energy (b) Potential Energy (c) Distance

Figure 8.20: Kinetic Energy, Potential Energy and Distance of PFHC SFU Control.

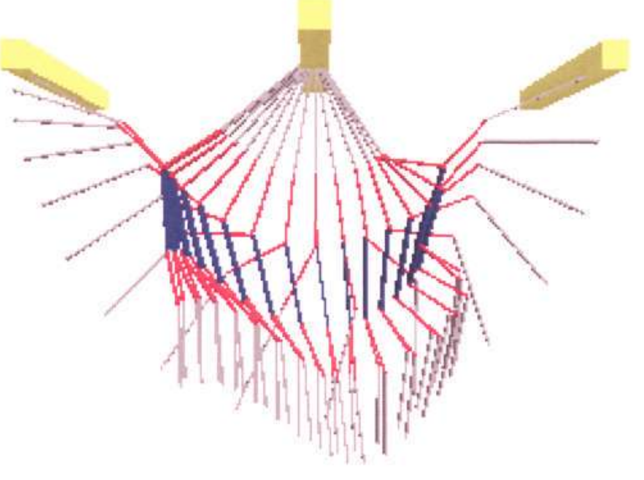


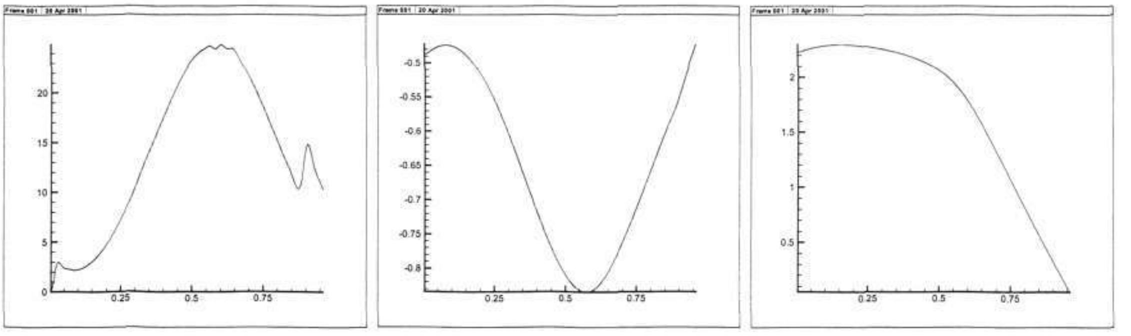
Figure 8.21: GRP Motion Results of 9-Link FPHC.

function of GRP.

The results are shown in Figure 8.21, where the brachiator has successfully caught the target, as shown in Figure 8.22 (c), and the minimum distance to the bar is less than 0.04 metres. The grasping gesture has been further improved when compared with the results of the SFU phase.

8.3.3 Summary of Heuristic Control

Among the three methods of heuristic control, PHC is appropriate for simple models, for example the 3-Link model, because the interacting interruptions between the links



(a) Kinetic Energy (b) Potential Energy (c) Distance

Figure 8.22: Kinetic Energy, Potential Energy and Distance of PFHC GRP Control.

would not be so serious as the complex model. But to a complex multiple links system, simply applying PHC is not appropriate, and it is difficult to assess the SFD motion which is a key problem to the final grasping motion.

This problem has been solved through the FHC that measures the effect of SFD and SFU on the final result of GRP. The multi-links system is able to adopt this FHC to achieve brachiation, but this causes a new problem in that we cannot control the intermediate posture, such as the postures during the SFD and SFU phases.

To solve this problem, the PFHC was designed to synthesize the advantages of PHC and FHC, and forsakes their disadvantages. The PFHC should be a sophisticated method for brachiation that can be applied to multi-link systems, as well as be able to control the intermediate postures.

After we finish adjusting the parameters of heuristic control, the general animator could apply this method to produce the required brachiation motion sequences, although it would take more time to calculate the proper torques than the tailored method. After this process, the generated torques can be directly and conveniently reused to produce the brachiation motion. Therefore, heuristic control possesses high automaticity.

On the other hand, if a normal animator wants to produce another different style of brachiation with the present heuristic control, there are two ways to achieve this requirement. One is to adjust the relative parameters. Another way is to redesign the objective functions. Both ways are not easy tasks for a final user. Therefore, the controllability of heuristic control is not sufficiently high.

8.4 Results of Interactive Control

Both tailored control and heuristic control possess high automaticity, however the controllability is relatively low. On the other hand, the interactive control possesses high controllability and less automaticity. In this section, the feature of interactive control is introduced with the experiments. The interactive control experiments are designed using the following four steps,

Step1: the free swing motion data is loaded first.

Step2: observe the performance of the motion sequences.

Step3: set a repeated interval for the interactive adjusting control point.

Step4: sequentially adjust the related link's control points.

Repeat step2 to step4, until a satisfactory brachiation motion sequence is obtained.

The experimental results of 3-Link interactive control are reported first, followed by 9-Link interactive control. Finally, a brief summary is presented.

8.4.1 3-Link Interactive Control

The interactive control was applied sequentially on the SFD, SFU and GRP phases. The torque of the trunk (TK) was first adjusted at the SFD phase to pump in kinetic energy. After that, the torque of the left arm (LA) was interactively controlled to coordinate with the trunk to perform a grasping motion.

Based on observing the present motion sequences, the results indicate that the grasping motion is not sufficient in the grasping phase. The related control points of the GRP phase were set as a repetitive interval, so that the grasping motion was repeatedly animated. This provides an opportunity to observe the grasping motion

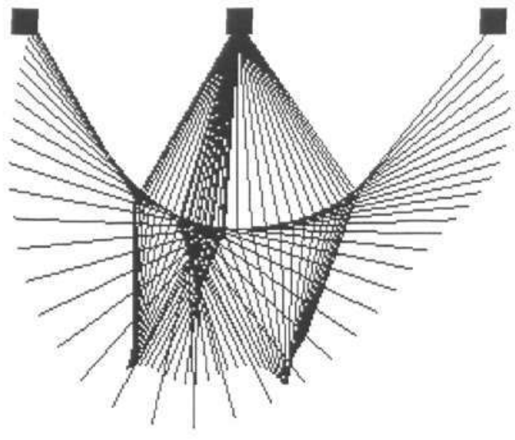
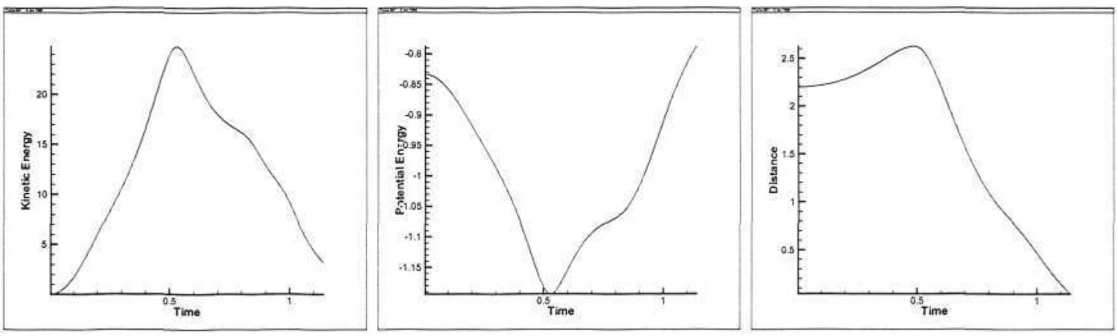


Figure 8.23: 3-Link interactive control motion results



(a) Kinetic energy

(b) Potential energy

(c) Distance

Figure 8.24: Kinetic energy, potential energy and distance of 3-Links interactive control

clearly. Meanwhile, the speed also was slowed down to allow convenient adjustment.

Finally, the expected brachiation animation can be acquired. The results are shown in Figure 8.23, which is a snapshot from the display screen. It indicates that the brachiator successfully catches the target bar. The feature of brachiation, the kinetic energy, potential energy and the distance between the palm of the grasping hand and the target are shown in Figure 8.24.

8.4.2 9-Link Interactive Control

To interactively control 9-link brachiation, we first set all torques to zero, i.e. we have free swing motion. Since the trunk is considered as the most important link during the swinging up phase, we first adjust it by increasing the value of the trunk's control points. The adjusted results are shown in Figure 8.25 (a). At this stage, the brachiator failed to grasp the target bar.

Both arms are the second most important components to the swinging and grasping motion. We adjust the control points of RUA, LUA and LLA using the keyboard. The adjusting results are shown in Figure 8.25 (b). It indicates that the brachiator has caught the target. But the motion of both upper legs is a little fast and over (more than 90 degrees that we wanted) at the GRP phase.

The control points of the lower limbs are adjusted to slow down the motion of the lower limbs. After we decrease the values of the control points at the GRP phase, the effects are reflected in Figure 8.25 (c).

Through the previous adjustment steps, the motion of grasping is still not satisfactory. After we further adjust the control points of the trunk and the lower limbs, much more better brachiating results are obtained, as illustrated in Figure 8.25 (d).

Over-Head SFOG Brachiation

In nature, Hylobates can perform different style of brachiation, where they move their grasping arm up and forward, rather than as we designed here swinging down-forward. To animate such brachiation is eventually not possible by directly applying the tailored control. But it is feasible to achieve it using interactive control.

Based on the previous experimental results, we apply a negative value on the control points of LUA during the SFD phase. The results are shown in Figure 8.26 (a). The adjustments directly make the left hand of the brachiator swing over-head during SFD, which is as we required, but it is violent at the SFU and GRP phases.

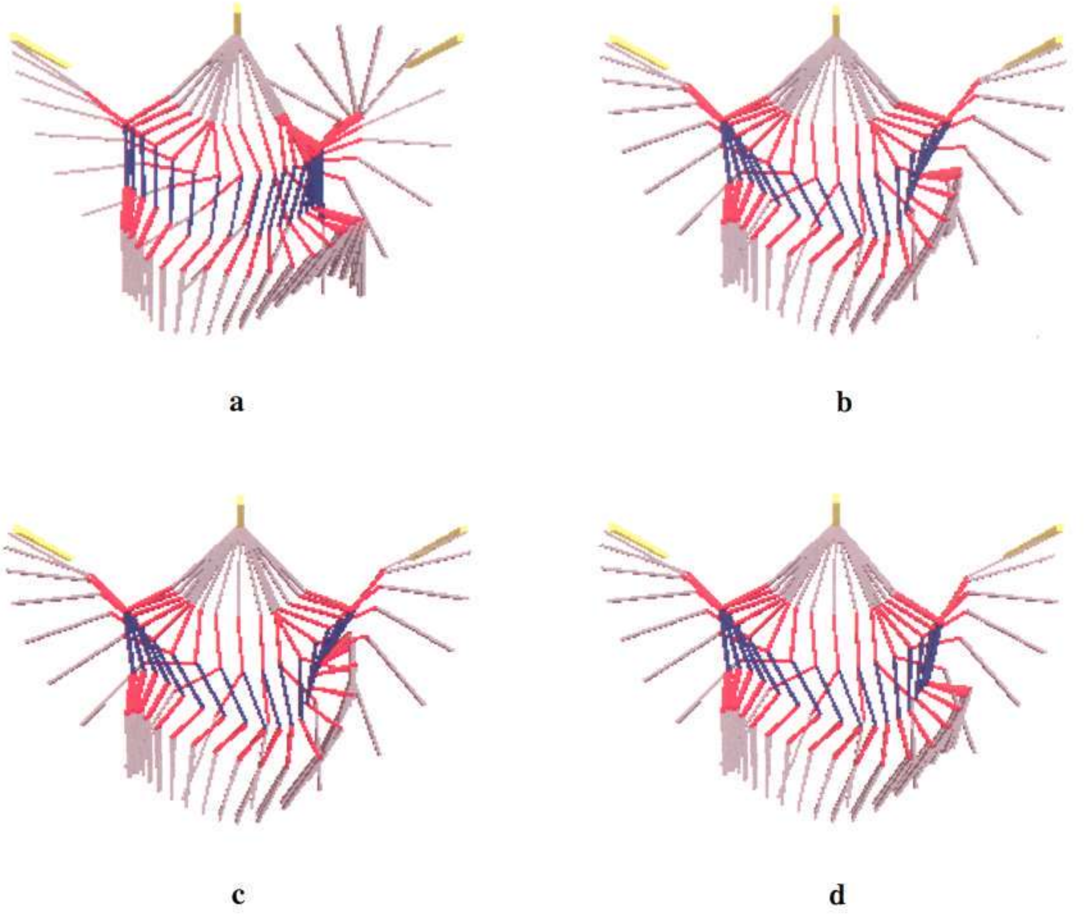


Figure 8.25: Results of Interactive Control. (a) adjusting the control points of the Trunk. (b) adjusting the control points of the Trunk, RUA and the Left Arms. (c) Adjusting the control points of the Trunk, RUA, the Left Arms and the Lower limbs. (d) Further adjusting the Trunk, the Lower limbs and the left arms.

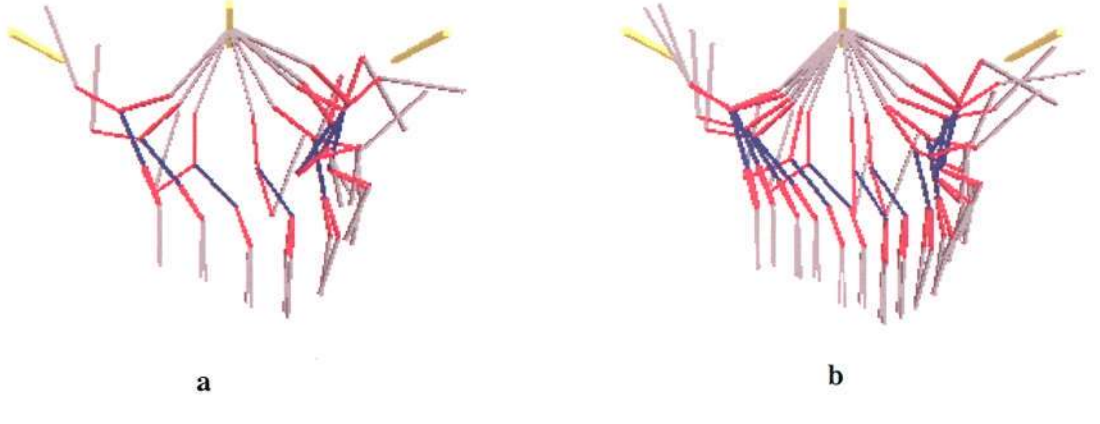


Figure 8.26: Results of swinging Left arm up-forward to brachiate by adjusting the torque of LUA and LLA.

We further adjust the control points of LUA and LLA, the over-head SFOG brachiation is achieved by simply adjusting the related DOF's control points, as shown in Figure 8.26 (b). If we want to achieve this distinct motion with tailored control, it is very difficult.

8.4.3 Summary of Interactive Control

We can achieve a desired motion by adjusting the torque curves of all DOFs, one by one and step by step, with the tools provided for the interactive control to ensure a better result will be obtained.

This has been confirmed by experimentation. When the structure of the brachiator is simple, it is very convenient to generate a variety of different motions by simply adjusting control points, and the results are physically-realistic. But when the structure of the brachiator is complex, for instance in the 9-Link model, the links can interfere with each other, and consequently it takes much more time to generate acceptable motion when compared to the simple structure.

Another serious restriction is that interactive control is only appropriate to the 2D system. In a 3D system, the interactive control would be poor. For instance to a one DOF 2D system, there are two motion tendencies to this link, one is to swing forward, while the other is to swing backward. These two motion tendencies directly map to the positive and negative torques exerted on this joint, so that we are able to apply interactive control. However, this mapping is more complex in a 3D system, say a joint with three DOFs, the motion tendency of this link is not able to be directly and intuitively mapped to the three torques of this three-DOF-joint. It would be a tedious job for an animator to interactively adjust the torque of each DOF to achieve anticipated motion sequences.

In our 2D brachiaton system, through this sieve method, the controllability has been improved by allowing every link to be directly controlled by increasing or decreasing the related torque. However, the automaticity is very low, because an animator needs to interactively adjust the torque on every link.

8.5 Results of Integrative Control

From the previous sections, it is apparent that tailored control and heuristic control possess high automaticity while interactive control possesses high controllability. The purpose of integrative control is to obtain high automaticity as well as high controllability by synthesising the three types of controls.

In this section, the experimental results of integrative control on a 3-Link model are reported first, followed by integrative control on a 9-Link model. A summary is presented at the end of each section.

8.5.1 3-Link Integrative Control

Since the experiments using 3-Link heuristic control have demonstrated a series integrative control method blended with the same heuristic controls in the three phases SFD, SFU and GRP, we will ignore the case of heuristic control integrating with heuristic control in this section.

Nevertheless, two typical integrating methods, heuristic control integrating with interactive control and tailored control integrating with interactive control, are illustrated with the goal motion Swing-Forward-Once-Grasp (SFOG).

Interactive-Heuristic Integrative Control

This experiment is based on the previous heuristic control experiments, from where the original control points were generated. We assume the grasping motion is not satisfactory. The interactive control is incorporated to adjust the motion.

Firstly, the interactive control reads the control points generated by the previous experiments using heuristic control and animates the results on the display screen.

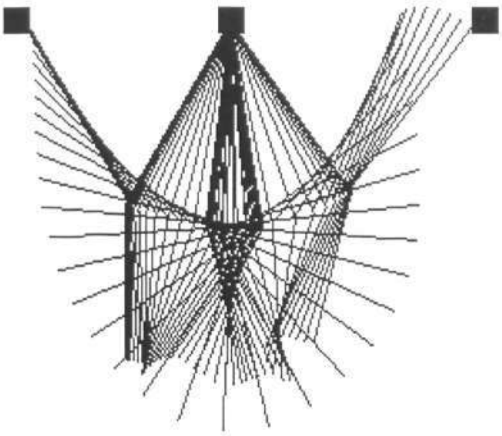
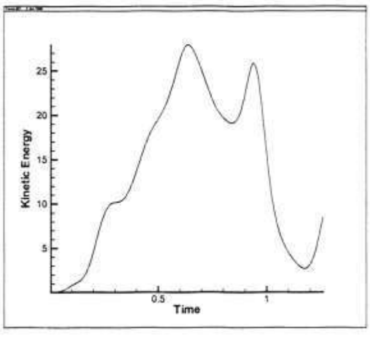
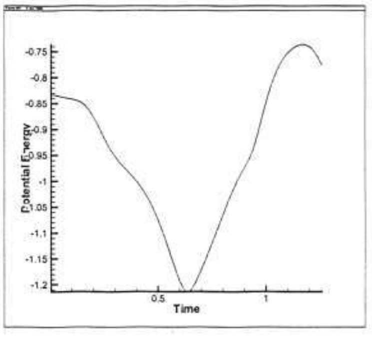


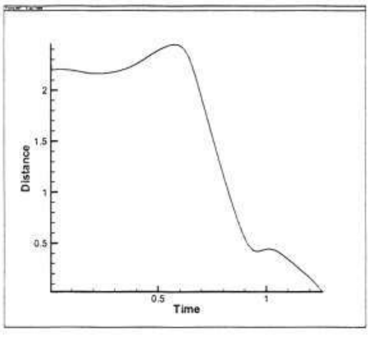
Figure 8.27: Results of 3-Link integrative control: Interactive-Heuristic Control



(a) Kinetic energy



(b) Potential energy



(c) Distance

Figure 8.28: Kinetic energy, potential energy and distance of each 3-Link integrative control : Interactive-Heuristic control.

Then the interval containing unsatisfactory motion which needs to be adjusted is determined. It is then set as a repeating interval and the motion sequences within this interval are demonstrated repeatedly using an adjustable and accessible speed.

After interactive control is applied on this interval to interactively adjust the control points to obtain a relative satisfactory and improved grasping motion, the results obtained are shown in Figure 8.27, with the corresponding energy and distance are shown in Figure 8.28$(a) - (c)$. The gesture of the GRP phase has been improved when compares with the results of heuristic control, as shown in Figure 8.11.

Interactive-Tailored Integrative Control

In this experiment, interactive control is integrated with tailored control to generate SFOG motion.

Observing the result of 3-Link tailored control, as shown in Figure 8.5, although the gesture of the grasping motion is as the requirement of the control, the posture of the SFD phase is not satisfactory. As the requirement, the brachiator should extend the body at the end of the SFD phase. This problem is to be solved with the integrative control, where interactive control will be applied to the SFD phase and tailored control applied to the SFU and GRP phases.

The results are shown in Figure 8.29. Comparing these results with the results of 3-Link tailored control, by applying interactive control to the SFD phase, the posture of the trunk has been improved. It is almost perpendicular to the ground at the end of the SFD phase. The postures of the SFU and GRP phases controlled by tailored control are also satisfactory as the requirement of the control. The energy and distance are shown in Figure 8.30 $(a) - (c)$.

8.5.2 9-Link Integrative Control

Although there are various integrative methods for 9-Link integrative control, the experiments focus on the three most representative methods, Interactive-Tailored Control, Interactive-Heuristic Control and Heuristic-Tailored Control.

Interactive-Tailored Integrated Control

In this section, tailored control and interactive control are integrated. Observing the experimental results of 9-Link tailored control the posture of grasping is accurately portrayed. The angles between the upper legs and the trunk, the upper legs and lower legs are at ninety degrees, just as required.

After the parameters of tailored control have been obtained, the process of produc-

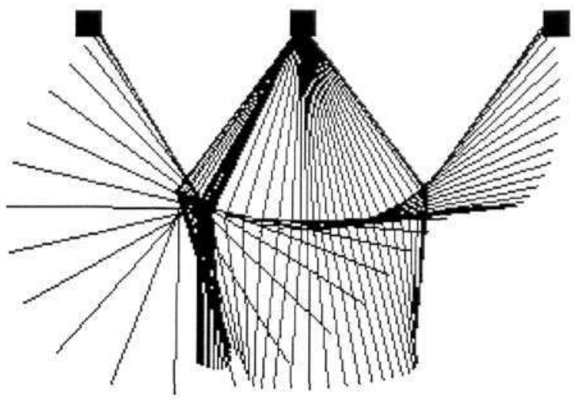
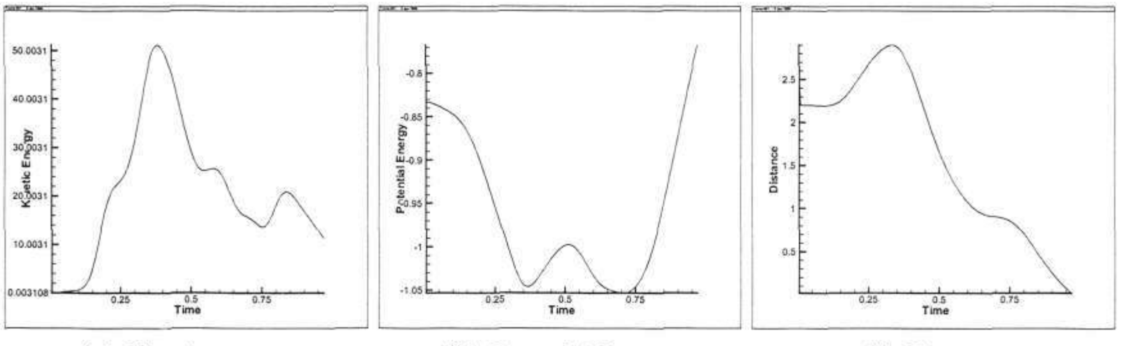


Figure 8.29: Results of 3-Links integrative control : Interactive-Tailored Control. Using the interactive control to the SFD phase, the posture of the trunk has been improved where is almost perpendicular to the ground at the end of the SFD phase and the postures of the SFU and GRP phases controlled by tailored control are also satisfactory as the requirement of the control.



(a) Kinetic energy (b) Potential Energy (c) Distance

Figure 8.30: Kinetic energy, potential energy and distance of 3-Link integrative control: Interactive-Tailored control.

ing the brachiation motion sequences is automatic and the result is reusable. However, the process has been fixed. If we need to generate other styles of motion sequences, even if the difference is very small it would be very difficult to achieve by applying the same tailored control. For instance, based on the above tailored control results, a director may have always been very happy with the results. But one day, he expects to generate a sequence of brachiation motion with the trunk and lower limbs not restricted to forming a ninety degree angle, but to be in a more relaxed way. The ability of tailored control to achieve this is very limited. There are only two ways it can be achieved using tailored control. One is to adjust the parameters of tailored control by trial-and-error, the other is to redesign tailored control, ie. reset the desired angles and desired velocities.

Alternatively, this is a situation which is suitable to integrative control that integrates tailored control with interactive control. The tailored control results of the SFD and SFU phases are first loaded, then interactive control is applied to modify the grasping motion during the GRP phase. Just by simply adjusting the control points of the grasping arm and the lower limbs of the grasping interval, it is possible to generate another grasping motion, as shown in Figure 8.31. Comparing this with the results of tailored control, as shown in Figure 8.7, the motion of brachiator looks more relaxed. The kinetic, potential energy and the distance are shown in Figure 8.32.

Interactive-Heuristic Integrated Control

In the 9-Link heuristic control experiments, we realised that, except for Phase-heuristic control (PHC), both Final-target heuristic control (FHC) and Phase-final-target heuristic control (PFHC), could successfully generate brachiation sequences. The results are quite satisfactory. However, in the actual production, say for the results of FHC, let us suppose that we need another kind of grasping motion, which may be, for example,

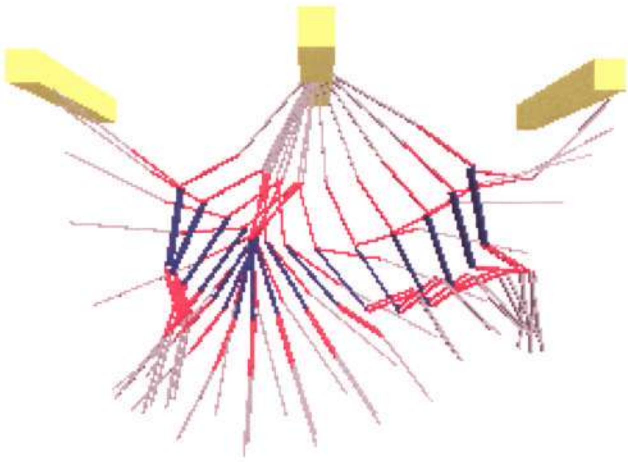
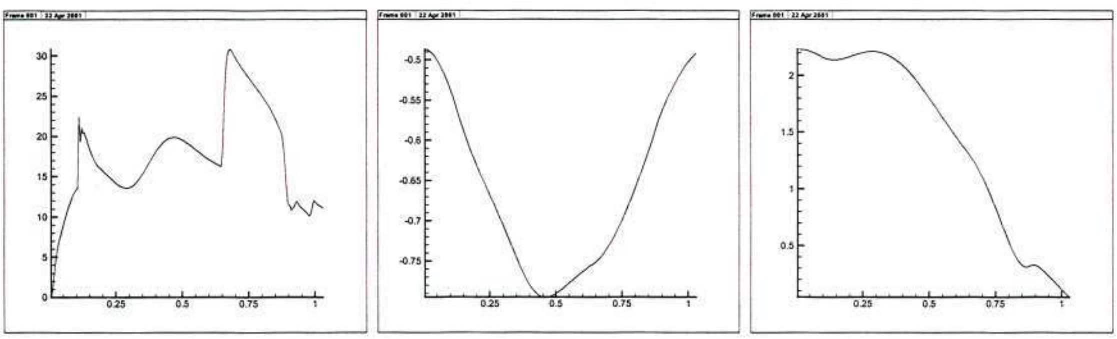


Figure 8.31: Result of 9-Link integrative control: interactive-tailored control.



(a) Kinematic Energy (b) Potential Energy (c) Distance

Figure 8.32: Kinetic energy, potential energy and distance of 9-Link integrative control: interactive-tailored control.

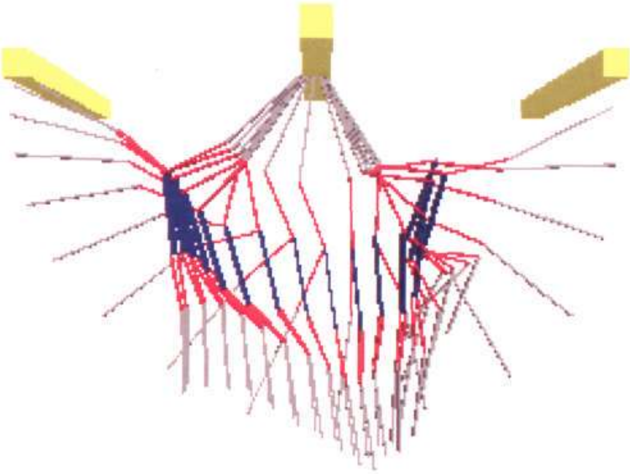


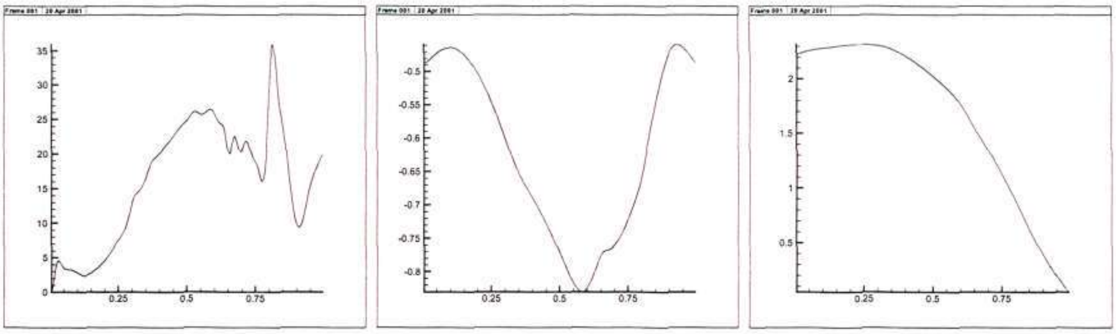
Figure 8.33: Based on the result of FHC, applying the interactive control, the motion result of integrating interactive control with heuristic control. It indicates the brachiator successfully catches the target with a more powerful posture.

more powerful. If we need to produce it using heuristic control, we need to redesign the objective functions of the GRP phase. This is almost an impossible task for a novice animator. Even to an expert, using an objective function to generate powerful motion is quite difficult. In this condition, it is time for the interactive-heuristic integrated control to be applied to the GRP phase.

Simply adjusting the control points of TRK, LUA, LLA and the lower limbs, we obtain a modified motion, as shown in Figure 8.33. It is more powerful when compared with the results of FHC. This is also apparent in Figure 8.34 where the potential energy is higher than the result controlled by heuristic control, as shown in Figure 8.16.

Heuristic-Tailored Integrated Control

Both heuristic control and tailored control possess high automaticity and poor controllability. From the viewpoint of improving automaticity and controllability, it is not necessary to integrate these two controls. However, to explore a new way of integrating, in this section, an attempt is made to integrate heuristic control with tailored



(a) Kinetic Energy (b) potential Energy (c) Distance

Figure 8.34: Kinatic energy, potential energy and distance to target of integrative control: interactive control and heuristic control.

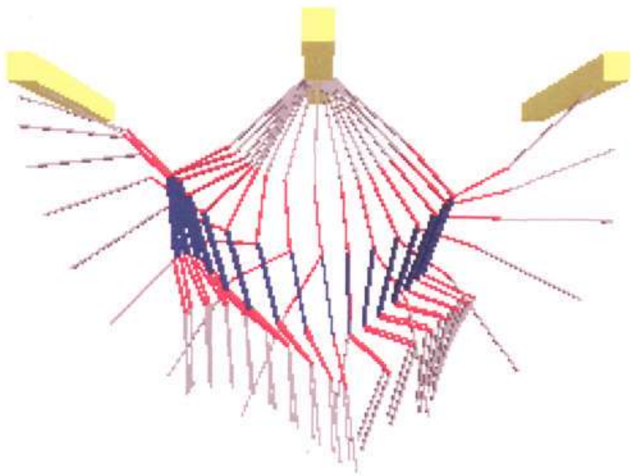
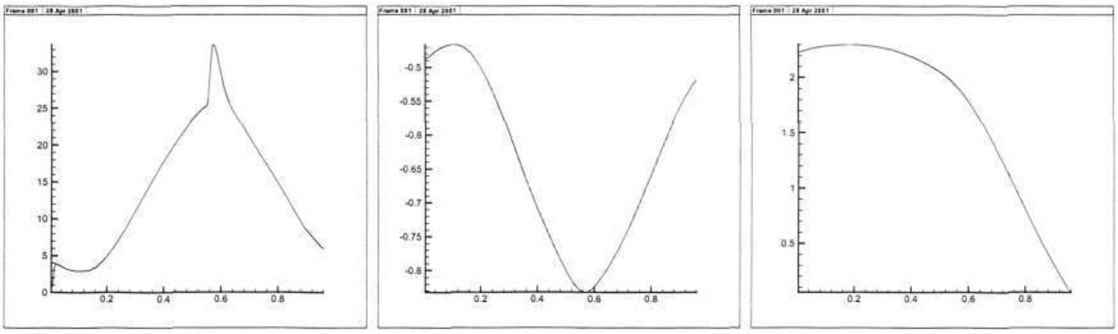


Figure 8.35: Results of integrative control: heuristic control and tailored control.

control.

After applying phase-final-target heuristic control onto the SFD, SFU and GRP phases, let us assume we wish to integrate tailored control onto the GRP phase. After integrating, the results are shown in Figure 8.35 and the energy and distance are shown in Figure 8.36, it indicates that the brachiator can finally catch the target with a proper and satisfactory posture. However, after the motion sequences have been generated, it would be very hard to readjust the motion sequences further.



(a) Kinetic Energy (b) Potential Energy (c) Distance

Figure 8.36: Kinetic energy, potential energy and distance to the target of heuristic control integrating with tailored control.

8.5.3 Summary of Integrative Control

By individually applying each control mechanism, the SFOG sequence can be achieved by tailored control, heuristic control or interactive control. But if they are blended together using integrative control, a trade-off between controllability and automaticity can be achieved.

Interactive control can be blended with either Heuristic control or Tailored control using both series and parallel methods. However Heuristic and Tailored control cannot be blended together mutually using the parallel method, despite the fact that heuristic and tailored control are closed-loop control and feedback control systems respectively, they can only be applied in series. From the viewpoint of improving the controllability, it seems unnecessary to blend them together when an animator is optimizing the control points, since they both lack controllability and possess high automaticity.

The experimental results of these experiments are summarised in the table 8.1.

8.6 Summary

Through a number of experiments, the tailored control and heuristic control of 3-Link and 9-Link models have been demonstrated to successfully produce convincing brachiation. The brachiators can grasp the target while maintaining a desired posture.

Although the automaticity is high, controllability is low.

Interactive control possesses high controllability and low automaticity. Applying interactive control on a simple model of a brachiator is a relatively easy task to produce a realistic brachiation motion sequence. But using interactive control on a complex model of brachiator, for instance a 9-Link model, is difficult.

The situation has been significantly improved by applying integrative control, which possesses high controllability and high automaticity. No matter whether the model is simple, like the 3-Link model or complex, like the 9-Link model, it is a sophisticated method which produced realistic animation of brachiation.

	E_k	E_p	Qualitative Evaluation
3-Link			
FreeSwing	24.7	-0.89	Lack of strength, grasping unsuccessful
Tailored	39.3	-0.81	Strong momentum, excessive power
Heuristic	27.9	-0.71	Grasping posture unnatural
Interactive	24.8	-0.79	Uniform motion, lack of momentum
Heur+Inter	28.0	-0.76	Grasping posture more natural
Tail+Inter	51.2	-0.78	Realistic motion achieved
9-Link			
FreeSwing	19.6	-0.63	No grasping motion, brachiation unsuccessful
Tailored			
Normal	28.0	-0.47	Brachiation is successful with a satisfactory grasping posture.
Hold-Arm-Control	47.0	-0.45	Hold-Arm-Control is efficiency, the brachiation is more powerful.
Heuristic			
PHC	70.2	-0.43	Grasping motion is failure.
FHC	24.1	-0.51	Brachiation is achieved however the intermediate postures are uncontrollable.
PFHC	24.8	-0.48	Brachiation is achieved however the intermediate postures are controllable.
Interactive			
Normal	27.7	-0.48	
Over-Head	27.2	-0.40	A normal SFOG brachiation is achieved with a satisfactory grasping gesture. A over-head brachiation is easily obtained by adjusting the relevant control points.
Heur+Inter	35.0	-0.46	The FHC brachiation is modified to more powerful by the interactive control.
Tail+Inter	30.2	-0.49	The brachiator's posture of GRP phase is interactively adjusted by the interactive control.
Heur+Tail	33.3	-0.52	

Table 8.1: Experimental Results: Quantitative and Qualitative Evaluation.

Chapter 9

Conclusion

9.1 Summary

This thesis defines two concepts, automaticity and controllability. These concepts provide new view points from which to analyse existing control methodologies within the scope of computer animation. The analysis includes most popular animation methods such as the traditional animation technique, kinematics keyframe technique and physically-based technique.

From the analysis presented in the previous chapters, we realise that as the automaticity is improved from the keyframe kinematics method to physically-base learning control, the controllability simultaneously reduces step by step. This tendency to reduce the controllability directly leads to a result where an animation control system could effectively generate a required animation motion sequence automatically. However, the control would be inflexible. It would be very difficult to apply the same control system to generate the same kind of motion sequence but with a slight difference, even if the difference is very small.

Unfortunately, this kind of requirement is frequently requested in animation movie production. For instance, a director proposes to generate a motion sequence for a certain character in a movie, meanwhile an animator designs a physically-based control to achieve the requirement. After that, if the animator needs to regenerate the same motion sequence but with slightly different style, what should the animator do with current animation method? He may need to redesign the physically-based control. As we know, that is not easy to accomplish. This can answer an interesting question: after physically-based animation techniques have been researched for almost 20 years and various motions can be animated, why are the traditional and kinematics keyframe techniques still popularly applied in the present famous animation studios rather than phycially-based animation technique?

The presently used physically-based control methods lack controllability. The goal of this thesis is to explore a new way to obtain high controllability and high automaticity based on the current existing physically-based methods.

To achieve sophisticated control which has high controllability and high automaticity, this thesis has focussed on brachiation. Brachiation is a special motion paradigm, except for the connection point, the holding bar, where the palm of the holding hand can interact with the external world, there is no other part of the body that can do so before it catches the target bar. There is no torque that the brachiator is able to apply onto the only connection point. The number of controllable DOF is less than the total number of DOF. Resulting in an unstable and underactuated system. To achieve the control task and produce realistic animation is therefore a difficult challenge.

Since brachiation is not a popular motion style and few researchers have focused on it, the literature survey of computer animation, robotic simulation and biomechanics of primate-like characters conducted and summarised uncovered relatively little previous work. The strengths and weaknesses of the few existing methods were identified and discussed.

As a result of the survey, the process of brachiation is detailed and broken down into several stages for animation. To achieve the target brachiation, although it was realised that a more complex model could generate more realistic motion, two different complexity brachiation models were designed and studied: a 3-Link model and a 9-

Link model.

Based on analyse of the target brachiation motion and different complexity models, high auotmaticity controls were proposed and evaluated using tailored control and heuristic control, and high controllability control, investigated using interactive control. To synthesise the controllability and automaticity, the integrative control was proposed to integrate the tailored control with interactive control and heuristic control with interactive control.

The first control for physically-based brachiation animation developed in this thesis is tailored control. To generate a sequence of realistic brachiating motions of the 3-Link and 9-Link models, the framework based on target feedback control was developed for generating realistic and smooth swinging trajectory motion of a primate creature. A catching feedback control was also integrated into the framework to produce precise and natural grasping action within a feasible region. The 9-Link model control proposed in this thesis is a completely new control for the holding arm. The functionality and behaviours of the essential controlled parameters were determined. Having developed the proposed dynamic module and control mechanisms, extensive experiments were conducted and reported to verify the computational effectiveness and realism of the brachiating motions of a primate-like creatures subjected to a few working conditions. Through the experiments, tailored controls for different complexity models were shown to be successful to control brachiation with high automaticity and low controllability.

Three kinds of heuristic controls were proposed and investigated: phase heuristic control (PHC), final-target heuristic control (FHC) and phase-final-target heuristic control (PFHC). Among them, the PHC was found to be suitable for simple models such as the 3-Link model but less suitable for complex model such as the 9-Link model. FHC is able to solve the problem in that it can be applied onto the complex model.

However its ability to control intermediate posture is not satisfactory. It is improved by using PFHC, which possesses the advantages of PHC as well as FHC. PFHC is appropriate for the complex model and it is suitable to control the intermediate postures during brachiation.

Interactive control possesses poor automaticity but high controllability. The experimental results indicate that it is convenient to adjust a physically-based motion sequence by simply adjusting the relative control points according to observations of the motion sequence. The major problem is that automaticity would be extremely poor as the complexity of the model increases. It would be a tedious task to purely apply interactive control to generate physically-based animation especially when the model is complex.

The most significant achievement in this thesis is that the sophisticated control called integrative control, has been proposed and investigated. Integrative control integrates the high automaticity control, tailored control, with the high controllability control, interactive control to synthesise both high controllability and high automaticity. In this thesis, the base conditions of integrating these different level controls have been reported. The integrating methods are discussed.

9.2 Contribution

- The primate brachiation has been comprehensively researched, some features of brachiation are reported for the first time; for instance, the brachiator adjusting the posture before releasing the hand to start brachiating. The two different complexities models, the 3-Link and 9-Link model, for different applications are innovatively devised. The 3-Link model is adequate to simulate brachiation motions in real-time for the requirement of the interactive simulation and on-line computer game. The 9-Link model is splendid for the fascinating and realistic brachiating motion to generate animation sequences for movie production and advertisements.

- To automatically produce brachiation motion, the high automaticity tailored control framework has been devised to facilitate the process of animating the brachiating creatures. The controllers developed for the brachiation models should be reusable and robust when subjected to different working conditions.
- To further improve automaticity, the heuristic control has been developed for the 3-Link and the 9-Link model. For example, based on the 3-Link heuristic control, three 9-Link heuristic controls were developed: phase, final-target and phase-final-target. The final phase-final-target heuristic control is more sophisticated.
- A high controllability control, the interactive control has been developed for interactively controlling brachiation. The interactive control provides real-time control to both the 3-Link and 9-Link models to adjust the torque curves of the brachiator to generate the physically-based animation.
- To integrate the high automaticity modules with the high controllability module, the integrative control method has been developed. Using the integrative control, both expert animators and amateurs are able to produce satisfactory brachiation motion sequences.
- Extensive experimental results have been reported to demonstrate the effectiveness and robustness of the high automaticity control: tailored and heuristic controls, the high controllability control: interactive control and both high controllability and automaticity control: integrative control.

9.3 Future Work

In the future, it is also desirable to apply the integrative control onto different kinds of animation to measure the robustness and suitability of this control.

In the 2-D condition, the integrative control is versatile to control physically-based animation. It is convenient to apply interactive control onto a joint having one DOF where the two motion directions are directly mapped to increasing and decreasing the torque of this joint. However, in the case of 3-D, a three DOFs joint, the mapping is indirect because the motion direction of the link connecting the joint is controlled by three DOFs. Directly applying interactive control to interactively adjust the torques of these three DOFs of this joint to control the link moving in a predicted trajectory is a challenging task. A more sophisticated interactive control for a 3-D joint are interesting topics for future research.

9.4 Publications

9.4.1 Published in Conferences

Papers published in Conferences:

- **Zhang Zheng, Wong Kok Cheong**. "Animating Brachiation".

  Proceedings of Eurographics'99, the 20th Annual Conference of the European Association for Computer Graphics. 1999, Milan, Italy, September 07 - 11, 1999.

  Related with 3-Link Brachiation Control described in Chapter 4 (Tailored Control), Chapter 5 (Heuristic Control), Chapter 6 (Interactive Control) and Chapter 7 (Integrative Control).

- **Zhang Zheng, Wong Kok Cheong**. "Details and Implementation Issues of Animating Brachiation".

  Proceedings of CAS '99, the 1999 Eurographics Workshop on Animation and Simulation '99. X23(1):123–129, Milan, Italy, September 7-8, 1999.

  Related with the 3-Link brachiation control parts described in Chapter 4 (Tailored Control), Chapter 5 (Heuristic Control), Chapter 6 (Interactive Control) and Chapter 7 (Integrative Control).

- **Zhang Zheng, Tony K. Y. Chan**. "Animating 9-Link Brachiation with Heuristic Control".

  Proceedings of GameOn 2003, the 4th International Conference on Intelligent Games and Simulation, 61-68. London, UK, 19-21 November 2003. EUROSIS 2003, ISBN 9-0773-8105-8.

  Related with the 9-Link control parts of Chapter 5 (Heuristic Control).

9.4.2 Submitted to Journals

Papers submitted to journals:

- **Zhang Zheng and Graham Leedham**. "Animating Brachiation Using a 9-Link Model and Integrating Tailored Control and Interactive Control". Submitted to: The Journal of Visualization and Computer Animation.

  Related to the work reported in Chapter 4 (Tailored Control), Chapter 6 (Interactive Control) and Chapter 7 (Integrative Control).

- **Zhang Zheng, Graham Leedham and Tony K. Y. Chan**. "Animating 9-Link Brachiation Using Heuristic Control". Submitted to: Computers & Graphics.

  Related to the work reported in Chapter 5 (Heuristic Control).

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%%
% This is the readme file of the thesis experimental results demonstration %
% Version 1.1 %
%%

Some experimental results of the 9-Link brachiation model are contained in this CD, including:

01_FreeSwing,
02_Tailored Control,
03_HeuristicControl ,
04_InteractiveControl and
05_IntegrativeControl.

The demonstrations are developed for Windows 2000 and XP using **OpenGL**. Please make sure you have installed OpenGL before you run the demo.

INSTRUCTIONS

1. To show each demonstration, just step into each directory and run *9L_Brachiation.exe.*

2. Press **Alt+F4** to stop demonstration.

3. Key **Left, Right, Up** and **Down** arrow keys to change the viewpoint.

4. Use the number keypad:
   8 , 9 pitch
   5, 6 roll
   2, 3 yaw

5. Use the **Home** key to reset the viewpoint.

If you have any problems running these demonstrations please contact Zhang Zheng at zhangzheng98@hotmail.com.

CONTENTS OF CD

01_FreeSwing :
The experimental results of free swing.

02_Tailored Control :
The experimental results of the tailored control.

21_TailoredControl_Normal :
The experimental results of the normal tailored control.

22_TailoredControl_HoldingControl :
The experimental results of HoldingArm tailored control.

03_HeuristicControl:

31_PHC:

The experimental results of Phase-Heuristic-Control.

32_FHC:

The experimental results of Final-Target-Heuristic-Control.

33_PFHC:

The experimental results of Phase- Final-Target-Heuristic-Control.

04_InteractiveControl:

The experimental results of interactive control.

NormalSwing:

Normal brachiation obtained by interactive control.

41_IC_LLA_TRK :

The experimental results of interactive control Left-Lower-Arm and Trunk.

42_IC_LLA_TRK_RUA :

The experimental results of interactive control Left-Lower-Arm, Trunk and Right-Upper-Arm.

43_IC_LLA_TRK_RUA_LUA :

The experimental results of interactive control Left-Lower-Arm, Trunk, Right-Upper-Arm and Left-Upper-Arm.

UpperArmSwing:

Upper swinging brachiation obtained by interactive control.

44_IC_UpperArmSwing_LUA :

The experimental results of interactively control Left-Upper-Arm.

45_IC_UpperArmSwing_LUA_LLA :

The experimental results of interactively control Left-Upper-Arm and Left-Lower-Arm.

05_IntegrativeControl :

The experimantal results of integrative control.

51_IntegrativeControl_Tailored+Interative:

The experimental results of integrative control: integrating tailored control with interactive control.

52_IntegrativeControl_Interactive_Heuristic:

The experimental results of integrative control: integrating heuristic control with interactive control.

53_IntegrativeControl_Heuristic_Tailored:

The experimental results of integrative control: integrating heuristic control with tailored control.