REAL-TIME DYNAMIC BALANCING AND WALKING CONTROL OF A 7-LINK PLANAR BIPED

James J. Troy
Research Associate

Iowa State University *
Mechanical Engineering Department
Ames, Iowa, 50011
troy@iastate.edu

ABSTRACT

Physically based modeling and feedback control techniques are used to simulate realistic motion for a planar 7-link biped. Multibody modeling, contact constraints, optimal balancing, and gait cycle generation will be discussed. Efficient multibody dynamics computation allows accurate motion to be simulated in real-time. A full state feedback linear-quadratic regulator control system is used to generate the joint actuator torques for balancing, and a state machine-PD controller is used for walking motion. The control system was designed to maintain stability on various surface environments and in the presence of external disturbances. Real-time interactive simulation software has been developed to allow the user to operate the biped system within a 3D virtual environment. Comparison of the 7-link biped simulation results to other planar biped models, as well as to human walking data, is presented.

1. INTRODUCTION

Walking is one of the most common human actions. We usually take it for granted and have difficulty explaining how we do it. But we can tell almost immediately if something doesn't look quite right when we see someone walking with a limp or when we watch an incorrectly modeled character in a computer animation. Natural looking human locomotion is an important problem to computer simulation and animation, but it is a difficult problem to solve. A solid foundation for finding a solution to this problem begins with the realization that accurate physically based modeling and feedback control are necessary to simulate realistic looking bipedal motion.

Research in the area of biped locomotion usually breaks down into these three areas: 1. biomechanics, 2. robotics and controls, and 3. computer graphics animation and simulation. Each field has a different perspective and specific goals. Biomechanics work usually focuses on experimental data collected by observing and analyzing human locomotion in a gait laboratory [5]. This work gives data on what happens during walking, but it does not reveal much on how to model and control it. Robotics and controls research in biped locomotion usually deal with non-interactive computer simulation [3] [12] [14] or with actual hardware devices [8] [10]. Unfortunately, these techniques don't tend to work well in a real-time computer simulation environment. Computer graphics animation of biped systems has relied mainly on keyframing, motion capture, and more recently on kinematics and dynamics [1] [2] [4] [6]. The trend of recent software development is to focus more attention on the high level path planning and put less effort into the low level complexities of modeling and control. The result is that many computer simulations tend to use oversimplified models and control systems. A more complete understanding of biped locomotion can be obtained by merging elements from all three fields.

Much of the current research in the area of dynamic biped motion simulation relies on simplified system dynamics. Although a few types of dynamic model simplification can be justified to some extent, oversimplifying system dynamics can result in motion that is inaccurate or even misleading. Some of the typical biped dynamics simplification include: kinematic replacement, non-coupled system elements, and rigid ground constraints.

In kinematic replacement, kinematic components are substituted for dynamic elements. For example, telescopic leg dynamics are sometimes used in place of an articulated knee [4] [6]. In this case, kinematics for an articulated knee are placed on top of the simplified dynamic leg motion. Even though the resulting walking motion may appear to vary only slightly from the motion generated by a more accurate leg model, the subtle differences are essential to our perception of walking, In addition, many aspects of walking and balancing cannot be controlled without an accurate leg model.

Another common oversimplification is the discarding of the force and/or moment coupling of some elements in a multibody system. Common applications of this type of simplification in biped modeling is to calculate the upper body motion after the lower body motion has been calculated, or by calculating the motion of the two legs independently and ignoring the coupling

* *Current address*: James J. Troy, Boeing Shared Services Group, P.O. Box 3707, MS 7L-43, Seattle, WA 98124, *Email*: jim.troy@boeing.com

effects between them. The disadvantage of this type of model definition is that disturbances in one part of the system will not effect the motion of the other parts.

Surface contact simplification is another area that can lead to unrealistic motion. Replacing the compliant reaction (soft constraint) of real foot-ground contact with a revolute joint (hard constraint) not only adds an unrealistic component to the model, but also requires the additional complexity of system reconfiguration and momentum transfer computations.

The goal of this paper is to present techniques for controlling coupled planar biped dynamics without the oversimplifications or reconfiguration complexity mentioned above. The focus here will be on issues involved in combining accurate and efficient multibody dynamics with feedback control and interactive computer graphics. The first topic will be a discussion of the multibody techniques used for development of mathematical models. Then balancing and walking control algorithms will be presented, as well as results of the interactive simulation of a 7-link biped as compared to other biped models and to human walking data. A balancing and walking sequence of the 7-link system used in this study is shown in Figure 1.

2. PHYSICALLY BASED MODELING

Modeling of physically based systems relies on mathematical equations that can be used to predict the motion of objects acted on by forces and moments. These equations can be solved to find the system states (position, velocity, and acceleration) as functions of time. The system response to external forces and moments is defined by the object's physical properties of mass and inertia, and by the system's geometrical configuration. The configuration, or arrangement, of a series of interconnected components forms a multibody system. Several methods exist for deriving the mathematical equations to predict motion for multibody systems. Formulation of the equations of motion for a 7-link biped model will be the focus of this section.

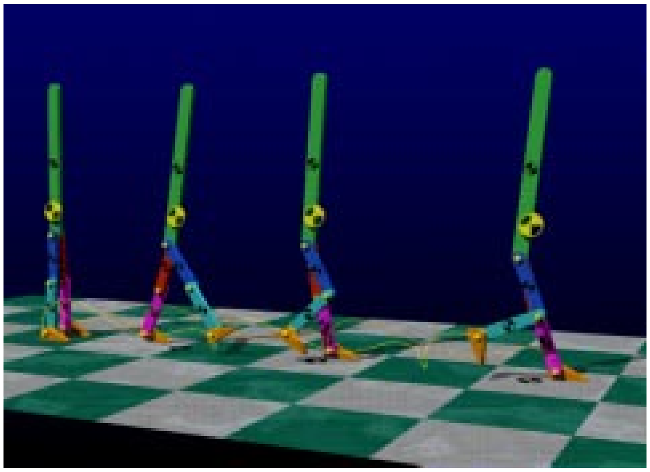

Figure 1. 7-link biped balancing and walking sequence (with foot path traces)

2.1 Planar Dynamics

The relative simplicity of planar dynamics allows the use of scalar multibody dynamics techniques. One of the most common methods for obtaining computationally efficient planar dynamics equations of motion is the Lagrange method.

Lagrangian dynamics methods [13] are based on the exchange of energy between kinetic and potential forms, with the external forces and torques represented by virtual work terms. The efficiency of Lagrange's method is due to the representation of system variables in terms of generalized coordinates. The advantage of using generalized coordinates is that the minimum number of equations are used, and solving for joint constraint forces is not needed. The symbolic representation of the multibody systems in generalized coordinates were derived using (EQ. 1).

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_i}\right) - \frac{\partial T}{\partial q_i} + \frac{\partial V}{\partial q_i} = Q_i \tag{1}$$

Where T is the scalar kinetic energy equation, V is the scalar potential energy equation, and Q is the virtual work. The nonlinear equations of motion are then written in matrix form (EQ. 2) and solved for in terms of the accelerations (EQ. 3).

$$A\ddot{X} = B \tag{2}$$

$$\ddot{X} = A^{-1}B \tag{3}$$

Where A is an $n \times n$ matrix (n = degrees of freedom), and B is a function of the generalized velocities, positions, control torques, and ground reaction forces. These equations can then be linearized about operating points for the control system design.

Linearization of the equations of motion involves using the first order terms of the Taylor series, where the linearization point, q^* , is selected by setting acceleration and velocity terms of the nonlinear system to zero and solving the resulting set of equilibrium state equations:

$$f_{q^*} + \left.\frac{\partial f}{\partial q}\right|_{q^*} \Delta q + \left.\frac{\partial f}{\partial \dot{q}}\right|_{q^*} \Delta \dot{q} + \left.\frac{\partial f}{\partial \ddot{q}}\right|_{q^*} \Delta \ddot{q} = 0 \tag{4}$$

2.2 Foot Model

One of the most important choices to make in creating multibody dynamics biped models deals with how to handle the foot-ground interface. Two main options exist: constraining the feet to the floor with revolute joints, or using spring-damper elements as constraints.

The joint constraint method requires a momentum transfer step to calculate the velocity changes due to the impulsive forces generated by contact. In addition, the system equations must be reconfigured at the point of contact to add or remove joints that attach the foot to the floor [3]. This procedure must occur every time the foot-ground contact status changes. Non-compliant constraints like this would only be acceptable for a device with hard feet that only come in contact with hard, high friction surfaces. This is an unrealistic assumption for human walking simulation.

2.3 Planar Biped Modeling

Several initial monoped and biped systems were modeled for testing and comparison purposes, some of which are shown in Figure 3. The modeling and control techniques developed for these simpler models were instrumental in the development of the 7-link biped model.

The primary system that will be discussed here is the 7-link (9-DOF) model of Figure 4, which consists of an upper body segment and two legs with articulated knees and feet. Control inputs are at the hip, knee, and ankle joints for each leg, for a total of six controlled torques. The coordinate systems for this model are given in Figure 5, with the additional foot variables shown in Figure 6. The complete multibody equations of motion are given in the Appendix of this paper. The physical parameters that were used for development and testing purposes are listed in Table 1. The mass and length values were chosen somewhat arbitrarily, only the relative sizes are important.

Table 1. Planar 7-link biped system parameters

Parameter	**L 1**	**L 2**	**L 3**	**L 4**	**L 5**	**L 6**	**L 7**
mass	2.0	0.5	0.5	0.2	0.5	0.5	0.2
length	2.0	0.5	0.5	0.3	0.5	0.5	0.3

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APPENDIX

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Haptics-e encourages the use of additional electronic materials in these forms: HTML and PDF documents, VRML geometry, GIF and JPEG images, MPEG movie files, ASCII text/code.

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