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Responsive Biped Character Stepping

When Push Comes To Shove

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Abstract—**In this paper, we propose a real-time approximation method for generating intelligent foot placement information for interactive biped characters. Our model uses an uncomplicated and efficient physics-based mechanism for generating fundamental pose information that can be used to construct the motions of a fully articulated dynamic character. The focus of this paper is a foot placement approximation method capable of producing balancing characters with dynamic characteristics. Furthermore, our model is straightforward to implement, computationally efficient, practical and robust, and ideal for time critical applications such as games.**

Keywords-character animation; balancing; inverse kinematics; inverted pendulum; foot placement; responsive; real-time

I. INTRODUCTION

Generating responsive dynamic characters that can handle unpredictable and unforeseen disturbances is challenging, interesting and important. This paper addresses the problem of how we can create character motions for responsive biped characters. Primarily, the problem of how a characters foot placement is fundamentally crucial for a biped to remain balanced when a disturbing force is applied. For example, if we push a virtual character then we need to know how to remedy this disturbance to ensure the biped remain upright and standing (or walking) (e.g., using ankle torques, or taking an intelligent footstep).

Creating characters using physics-based methods produces interactive and responsive motions that are flexible and non-repetitive. Furthermore, the characters motions can be easily altering by modifying the physical attributes instead of relying on fixed libraries of key-framed data. Moreover, the physics-based model we present in this paper is flexible enough to be applied to characters of varying sizes and masses to produce an assortment of characterized styles.

Making human-like characters respond realistically and naturally to disturbances is difficult due to the high degree of complexity and flexibility that is possible. Furthermore, approaches that use inverse kinematic methods in conjunction with key framed data to emulate responsive character effects can fail to produce physically accurate results. Moreover, pre-canned animated characters systems produce repetitive, predictable and unresponsive motions that lack the ability to adapt to unforeseen circumstances

The inverted pendulum (IP) has long been a popular solution for creating dynamic and responsive physics-based information for character systems. The IP method is a simplified mechanism for approximating dynamic characteristics of a biped. The model replaces the complex articulated character configuration with a simplified point mass approximation that is balanced on massless legs. This simplistic model generates reliable dynamic information for balancing bipeds but does not provide decisive data about the feet, how they transition, or how they handle constraint conditions.

However, we use the basic IP model and extend it to include additional foot information that can be used to produce a more accurate physical character biped (e.g., foot orientation, foot torque, position transition paths).

The key points of our approach are the development of a robust and computationally efficient foot placement base controller model that can be used to produce natural responsive character motions.

A. *Motivation*

The motivation for this research is aimed at producing straightforward and minimalistic approximation methods for generating responsive physics-based character motions for dynamic environments and time critical systems such as games.

B. *Contribution*

The contribution of this paper is a practical, computationally efficient, and robust foot placement approximation method for balancing bipeds that can be used to create realistic, responsive, character motions.

The novel approach focuses on simplifying the biped foot support region (e.g., to use spheres and capsules) to produce approximate foot placement and balancing information (e.g., position, orientation, path trajectories) in conjunction with an intelligent physics-based model to generate dynamic character motions.

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C. *RoadMap*

The roadmap for the rest of the paper is as follows. Section II gives a broad overview of the related research; Section III presents a system overview of the interconnected components and our approach. Then Sections IV to Section VI describe the individual components and their workings. Section VII presents our initial results. Section VIII discusses limitation factors. Finally, we conclude with Section IX that discusses further work and conclusions.

II. RELATED WORK

Physics-based biped characters with responsive characteristics have been investigated across numerous fields (e.g., computer graphics and robotics).

A. *Computer Graphics*

Komura [1] simulated reactive motions for running and walking of human figures, while Zordan [2] simulated characters that responded automatically to impacts and smoothly returned to tracking and later [3] presented work for combining existing motion capture data from humans to produce physics-based responsive motion segments that responded to varying force disturbances (demonstrated using a martial art test bed).

Shiratori [4] developed a novel controller that could generate responsive balancing actions; while Tang [5] modified interactive character motions for falling with realistic responses to unexpected forces.

McCann [6] presented that blending between various motion capture segments to produce responsive character motions. Additionally, Arikan [7] did similar work on generating how people respond to being pushed around.

In the same way, a method similar to the one we presented in this research paper was also offered by Singh [8] who focused on a simplified footstep model for simulating crowds by means of circle foot approximations and local pelvis space to generate foot position and orientation information. Wu [9] presented a method for controlling animated characters by modifying their foot placement information so that it was physically correct.

B. *Robotics*

Emphasising some of the relevant work in the field of robotics that contributed to the development of responsive biped controllers we outline a few interesting and important papers. Shih [10] developed a straightforward model for enabling characters to responds to small disturbances. While Stephens [11] and Pratt [12] developed controllers that could generate motions to recover from a range of push disturbances.

III. SYSTEM OVERVIEW

In our approach, we use a low-dimensional base controller for estimating key information for highly complex articulated characters that enable us to determine intelligent foot place information to remain balanced and upright. The low-dimensional controller calculates information on where to place the characters foot to produce the desired upright motion. The controller can be iteratively updated to give corrective feedback information to ensure the resulting motion is achieved (e.g., due to minor force disturbances and numerical inaccuracies).

We implement the basic inverted pendulum model and incorporate additional information to gain greater control through feedback from the feet. However, while this paper primarily focuses on the feet to gain additional control, alternative research has been done to extend other areas of the inverted pendulum. For example, Kenwright [13] extended the inverted pendulum model to include an elongated 3D rigid body to produce additional postural information in collaboration with further control possibilities.

The inverted pendulum model presents an ideal method for emulating a characters leg since the human muscle is mechanically analogous to a spring-damper system; consequently, stiffness and damping factors can be calculated to mimic a persons limbs and how they would respond (see Figure 1).

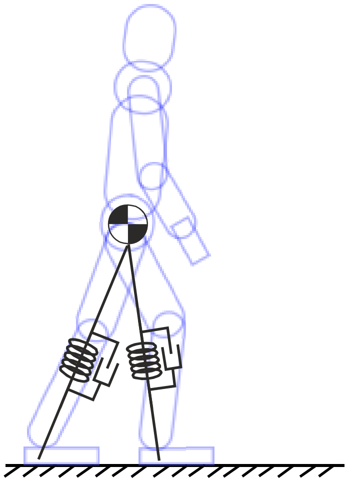

Figure 1. Illustration of how the inverted pendulum is used to represent a character's mass and legs.

The system produces physically realistic responsive character motions, which have the added advantage of being computationally simple and robust.

Each foot's support area is represented by a circle that is projected onto the ground. When both feet are in contact with the ground the support area changes to a capsule shape. Projecting the Centre of Mass (CoM) onto the ground we can use these simplified support regions to give us essential balancing information. Hence, as the inverted pendulum changes between the single and the double support phase over time we can gather additional information to give corrective balancing and control feedback values (see Figure 2).

Furthermore, since we add a support region to the feet of the inverted pendulum this allows us to induce an ankle torque to correct small disturbances without needing to take a corrective footstep. Moreover, this ankle torque provides a means of correcting minor disturbances due to any approximation errors (e.g., ankle torque can introduce corrective balancing and steering parameters).

The logic is managed using a finite state machine. The state machine examines the information from the inverted pendulum model to determine the next state of action that needs to be performed (e.g., apply ankle torque, take corrective step, or continue walking). The state machine has three primary logic components shown in Algorithm V-1.

The inverted pendulum on its own is a very minimalistic physics-based controller that has little overhead and is capable of producing practical, robust and reliable data for balancing and locomotion; hence it is ideal for time critical systems (e.g., games). Furthermore, the inverted pendulum is able to handle uneven terrain (e.g., stairs and slopes). Additionally, by altering the placement of the foot position and the urgency that the foot reaches its target position can produce numerous styles of walking.

IV. POSE TRACKING

The base inverted pendulum model gives us information to remain balanced and upright (i.e., either standing, walking or running).

A. *Intelligent Foot Placement*

The basic IP model does not address the issue of how the feet should be moved or orientated between foot transitions. The IP only calculates the desired final foot positions based on the point mass's position and velocity.

1) Do We Need Feet?

For a character to be useful it needs feet; it is not possible for a passive platform to stand in a single, stable position if it is supported by only two points; however, a dynamic system can balance on two points like stilts if the supporting points are allowed to move and are controlled by a sufficiently sophisticated control system. *The stiff-legged stilt character must remain in a continual state of motion to maintain balance* (see Sias [14] for further details on why we need feet).

2) Determining the Support Polygon

The support polygon represents the support area for the feet used to keep the character balancing and upright. Without the support polygon the character would constantly need to move to remain balanced. Exact approaches of exist for calculating the feet contact area. These exact methods use complex contact polygon constructions or simplified rectangles. Our method uses a simplified approximation of circles to represent each foots support region and a capsule when both feet are in contact with the ground. The circle-capsule method of calculating the support region is a computationally simple approach of generating valid foot approximation information (see Yin [15] for detailed explanation of support regions and more exact methods).

3) Feet Location Comfort Factor

The dynamic model determines the necessary foot placement information to remedy any force disturbances and remain upright. However, the resulting foot placement movement can result in the characters feet being left in an uncomfortable and unnatural looking pose. To remedy this we include an additional logic step to determine if the character has reached a stable state and needs to take a corrective step to return the feet to a more comfortable positions.

4) Foot Placement Constraints

The final calculated foot position and orientation had limiting constraints imposed upon them. This ensured they never stepped on another foot or in an undesired location. For example, if we wanted to avoid the foot being placed in a hole we would select the next closest point. The corrective step would then go ahead using the alternative position. However, if the corrective step was not able to balance the model then the state logic would again repeat the corrective step calculation based upon the new position of the body and feet. This process is automatic and repeats until it reaches a stable balancing state.

B. *Body Orientation*

The feet and centre of mass are moving around to keep the character upright and balanced. Nevertheless, the body stores the desired direction from which all other orientations are calculated (see Figure 3). The feet will always use the parent body as the reference location to determine the final orientation of the foot.

Furthermore, as the characters main body turns and rotates the ideal resting location for each foot is modified so that the feet have to take corrective steps to match the desired orientation of the pelvis.

V. BASE CONTROLLER

The base controller for determining where to place the characters foot to achieve walking or halt motion is based upon the spring loaded inverted pendulum (SLIP). The SLIP model approximation represents the mass properties of the character as a single particle point mass. This single point mass is balanced upon mass-less spring-damper sticks that mimic the legs and muscles of a human.

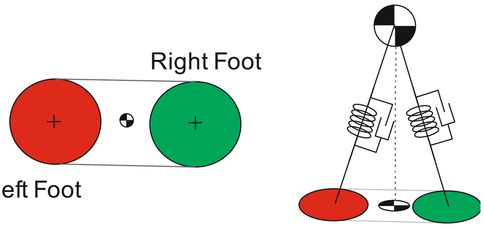

Figure 2. Inverted pendulum, individual foot regions and combined foot region.

Figure 2 shows the base controller model that generates the crucial balancing and locomotion information for our biped character. The key pieces of information are the pelvis positions and feet positions. The inverted pendulum can predict where to move the feet to maintain a persistent stable walking motion or to halt movement in any direction.

Initially, it positions the centre of mass above the centre of pressure (CoP), from there on, then it lifts its front body up, while compensating with the lower body to maintain the CoM above the foot position.

Due to the dynamic feedback of the model, any disturbances which might arise (e.g., pushes, trips, uneven terrain), will be fed back into the base-controller which will attempt to compensate for them in further steps.

A. Controller Constraints

For the base controller to achieve an upright posture, a number of constraints must be imposed.

It must be possible for the controller to place its centre of mass above its foot position. While the default model has massless legs so can move the leg with least mass instantly the speed that a leg can reach its target destination must be constrained.

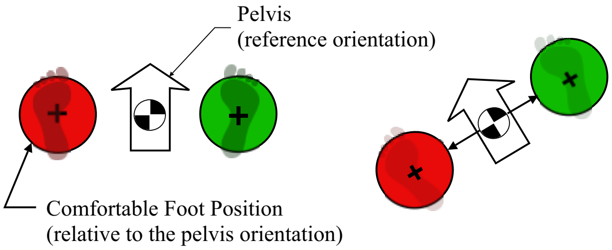

Figure 3. Illustrating the comfortable positions the feet will return to after a disturbance or when idling.

B. Foot Swing

When the new foot's position and orientation has been calculated, it is necessary to generate a path that the foot must travel to reach its target. While initially an elliptical arc was used based on an uncomplicated Bezier curve, it produced an unnatural looking stepping action.

However, analyzing the walking motion of a biped character, it was found that the path of the foot shoots up and exponentially decays towards the target location due to the toe and heal (see Figure 4).

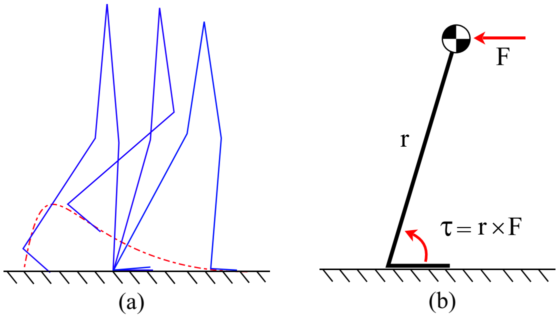

Figure 4. (a) Foot swing phase for a human walking. (b) Ankle torque is used to steer and control the upper body.

An approximation that mimicked a more realistic path for locomotion and corrective foot placements was accomplished using a Bezier path with the peak curve shifted towards the beginning (matching the path shown in Figure 4).

C. Foot Logic

The simple decision logic is iteratively updated based on the state machine logic to determine the current state of the biped and if it is necessary to take any corrective actions (see Algorithm V-1).

```
Foot Placement Logic
Identify if we are Walking or Standing
   When placing the foot we need to decide if we want to 'halt'
   motion (e.g., respond to a push disturbance) or if we are
   continue walking

Three Options
A. Balance using feet torque (are we comfortable ?)

B. Take a corrective step

   Two sub-options
   1. Prevent fall
        + Identify which foot has the most weight (e.g., which
          side of the pelvis is the CoM located).
        + Final orientation of the foot is taken from the
          reference pelvis orientation.

   2. Comfort (e.g., cross legged)
         +After a disturbance or previous corrective step we may
          need to take another corrective step (recursively) to a
          more comfortable foot location pose

      Comfort Logic
         + Is the foot within its comfort region and facing the
           same direction as the pelvis?

C. Force is too much to recover from - we must fall.
     + Take protective actions (do not turn into a limp ragdoll) -
       place arms in the direction we are falling.
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Algorithm V-1. State decision logic for determine the course of action based on disturbances.

VI. INVERSE KINEMATICS

We use inverse kinematics to take our low-dimensional model and map it onto a complex articulated character. In addition to the IK generating the desired primary and secondary joint angles, it also imposes the physical joint angle constraints to ensure the model always produces legal human poses. This is done by using the primary key elements from our controller to keep the character balanced and physically correct that are passed along to the IK end-effectors.

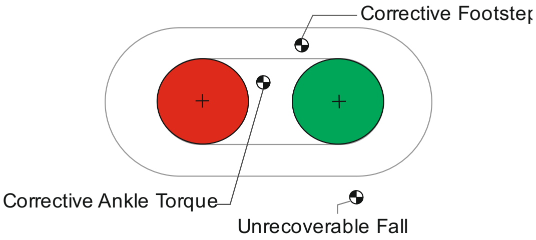


Figure 5. Response decision.

A. Biped Model

The mechanical functioning of the biped is modeled as a series of multiple rigid segments (or links) connected by joints. This series will also be called a kinematic chain.

As shown in Figure 7b, the body is represented by 16 segments and is connected using 16 links. The character gives us 36 degrees of freedom (DOF).

Joints such as the shoulder have three DOF corresponding to abduction/adduction, flexion/extension and internal/external rotation (e.g., rotation around the x, y and z axis).

It is convenient to note that a joint with n DOF is equivalent to n joints of 1 DOF connected by n-1 links of length zero.

Thus, the shoulder joint can be described as a sequence of 3 joints. Each separate joint have 1 DOF and 2 of the joints are connected with zero length links.

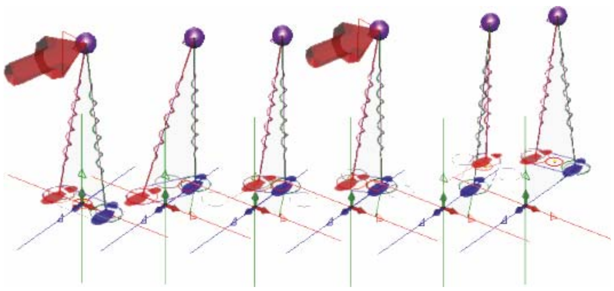
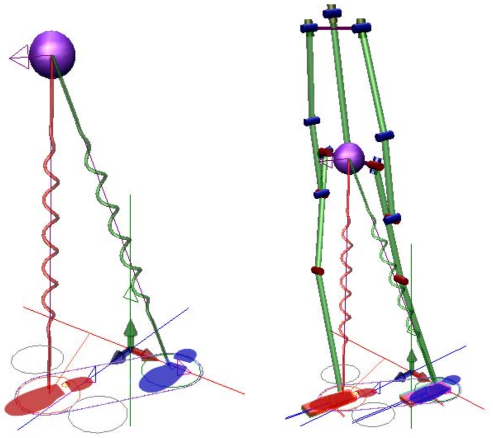


Figure 6. Illustrate the basic model standing before being pushed twice and being forced to take corrective steps before returning to a relaxed stance.



(a) (b)

Figure 7. Simple spring loaded inverted pendulum and full skeleton model used for testing.

Figure 8 shows the skeleton pose and Figure 7b shows the model combined with the inverse pendulum model. The foot was set as the root of the IK solver. The IK system had five end-effectors (i.e., head, pelvis, right-hand, left-hand and left-foot). The base controller would feed information to the feet and pelvis.

VII. EXPERIMENTAL RESULTS

The controller generates essential information for the biped character to stay upright. This information is passed to the IK end-effectors locations to produce the full character biped motion.

With inverse kinematics and data-driven approaches, the generated motions are not physically accurate. These approaches usually fail to produce realistic and responsive balancing motions. Furthermore, non-physics-based models, the characters dimensions cannot be modified without repercussions and do not reflect the strength of the characters muscles

The preliminary work shows promising results and great potential for simulating crowds of characters. The model is minimalistic and computationally efficient. The largest computational overhead was generating the inverse kinematic skeleton pose from the end-effectors information generated by our inverse pendulum model and foot logic algorithm (see Figure 7 and Figure 6 for simulation screenshots).

VIII. LIMITATIONS

Our model only focuses on upright biped characters with an emphasis on foot placement information. Hence, a larger repertoire of actions would be needed to make this a viable option for virtual gaming environments (e.g., getup, climb, fight, and dance).

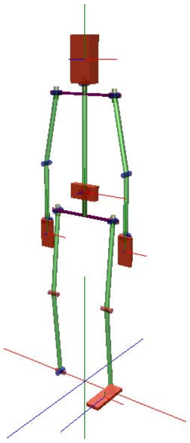


Figure 8. The joint configuration with the support foot set as the base of the IK (i.e., right foot in the figure).

IX. CONCLUSION AND FURTHER WORK

The base controller model with our foot support area approximation is a computationally simple, robust, and flexible method of controlling a biped and generating self-directed responsive motions. Furthermore, the model can be used either in real-time environments or in an off-line tool to tweak key framed data to be physically correct.

The information provided by the feet is crucial for generating upright balancing biped characters and has shown promising potential for further investigation (e.g., adding in heal-toe shifting during landing, better steering control). In addition, due to the models dynamic ability to recover from disturbances, cope with uneven terrain (e.g., stairs, obstacle avoidance), and handle foot placement constraints (e.g., does not have to be the desired foot placement target) it solves a number of problems for creating biped motions with intelligent foot information for various types of virtual environments.

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