Beyond Keyframe Animations

A Controller Character-Based Stepping Approach

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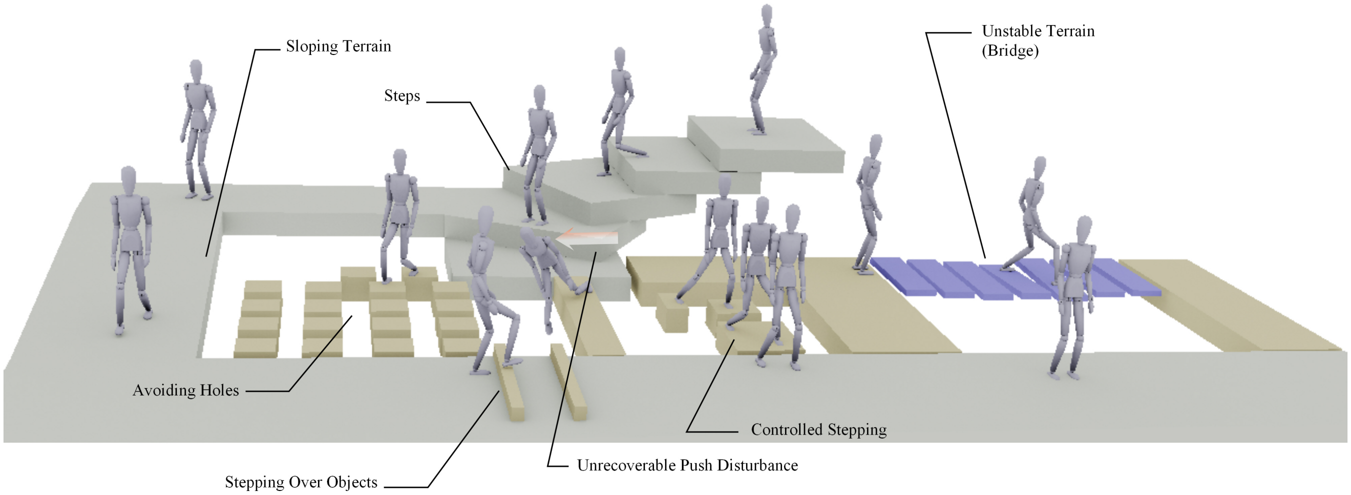

Figure 1: *Stepping results obtaind with our method, showing a biped character navigating a complex terrain with stairs, sloping ground, holes, and a bridge, while stepping over immovable objects. The stepping contribution produces precisely controlled dynamic upright standing and walking motions.*

Abstract

We present a controllable stepping method for procedurally generating upright biped animations in real-time for three dimensional changing environments without key-frame data. In complex virtual worlds, a character's stepping location can be limited or constrained (e.g., on stepping stones). While it is common in pendulum-based stepping techniques to calculate the foot-placement location to counteract disturbances and maintain a controlled speed while walking (e.g, the capture-point), we specify a foot location based on the terrain constraints and change the leg-length to accomplish the same goal. This allows us to precisely navigate a complex terrain while remaining responsive and robust (e.g., the ability to move the foot to a specific location at a controlled speed and trajectory and handle disruptions). We demonstrate our models ability through various simulation situations, such as, push disturbances, walking on uneven terrain, walking on stepping stones, and walking up and down stairs. The questions we aim to address are: Why do we use the inverted pendulum model? What advantages does it provide? What are its limitations? What are the different types of inverted pendulum model? How do we control the inverted pendulum? and How do we make the inverted pendulum a viable solution for generating 'controlled' character stepping animations?

1 Introduction

Human avatars are a common site in interactive virtual worlds, such as video-games and training simulations. However, creating physically accurate, controllable, adaptable, and interactive biped character animations in real-time that mimic real-world humans is challenging. In particular, the fundamental animations that are essential for a virtual character to navigate and explore its environment, are walking, standing, and running. While these motions can be recorded from real-actors using motion capture or created by key-framed based techniques, they can have problems adapting to complex terrains and disturbances, such as pushes and trips. Furthermore, when the character's features change (e.g., height and walk stride) it can be difficult to adapt the motion capture data accordingly.

Balanced Stepping Motion The goal is not to generate a biped with perfect balance, but to intelligently recover from it when it is lost in a realistic way, over and over again. Human stepping movement is smooth, realistic, and life-like; since, in reality, a human is always moving and is never statically still (e.g., they possess small swaying movements). In retrospect, a human's movement is typically graceful and comes from "dynamic" rather than "static" stability. *Merely steering the character by pushing it with forces in the desired direction will produce unrealistic motions.* For example, if we make the virtual character timidly extend his free leg in the direction of navigation before committing any weight to it, while constantly maintaining balance, will produce movements that appear robot-like and unnatural. This motion does not feel fluid and never takes flight; making the character appear scared of losing balance. *In reality, a human character relishes its dynamic ability without any effort or worry.* A life-like character allows their full body weight to wonder away from their point of static balance in any direction, and is able to recover and adapt to the situation. As the character falls further off-center, he must push harder into the floor to keep the motion horizontal and stretch the anchored leg further and more quickly to compensate for his hypotenuse. Achieving this

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smoothly and in a life-like way demands both active muscle power and precise control. For example, as a character steps during walking he will fall away from his horizontal center-of-mass towards his new one and barely show any imbalance while delivering a deliberate fluid stepping movement.

Challenges So why is it so challenging to reproduce life-like human movements in realtime 'and' without key-frame data? Why has it eluded us for so long? To begin with, realism is especially difficult, as a particular character model gives rise to a large set of possible motions with different styles. Even if robust and stabilizing control laws can be found, it is challenging to construct those that reproduce the intricate and agile movements we observe in nature. Then there is model complexity, since a character can have an extremely high number of degrees-of-freedom, it makes the search for the appropriate control parameters hard. Although continuous numerical optimizations techniques can cope with large search spaces, the stringent demands of interactive applications make it clear that optimization cannot solely be performed at the time control is needed. Also, the discontinuous non-linear character workspace (e.g., joint limits and contacts) restrict movement within a certain region of three-dimensional space; these constraints are difficult to maintain in real-time simulation systems, such as games. Furthermore, frequent ground contacts create a highly discontinuous search space rendering most continuous controller synthesis methods ineffective at planning over longer time horizons. Finally, dynamically simulated characters are difficult to control because they have no direct control over their global position and orientation (i.e., underactuation). Even staying upright is a challenge for large disturbances. In order to succeed, a control law must plan ahead to determine actions that can stabilize the body.

This paper compares and explains the different character-based pendulum stepping models and their associated control mechanisms. We then present a novel real-time stepping model for generating full-body biped motions on-the-fly without key-framed data that can be carefully controlled while remaining responsive and robust (e.g., the ability to move the foot to a new support region at a controlled speed and trajectory). We demonstrate our models ability through various simulation situations, such as, push disturbances, walking on uneven terrain, walking on stepping stones, and walking up or down stairs. We extend the low-level stepping model to create coordinated full-body motions. Our system produces directable steps that guide a character with specific goals (e.g., follow a particular path, or place feet at specific locations).

Contribution The key contributions of this paper are:

- We evaluate and compare the different character-based pendulum stepping models and their associated control mechanisms
- While the IP model provides a fast robust stepping solution; we address the highly crucial factor of *control* so that the solution can be of practical importance and useful in future state-of-the-art implementations (e.g., carefully placing the foot at specific locations while walking at different speeds and remaining balanced and in control - even during changing terrain and random external environmental disturbances)
- We produce a customizable pendulum stepping system that provides better control and stability, using different feature enhancements, such as a variable leg-length and ankle-torque

2 Related Work

The inverted pendulum (IP) in the context of character-based systems with its various modifications and enhancements is a popular technique that has been exploited across different fields of research since it provides a computationally fast and simple balancing mechanism. We illustrate and explain the different character-based pendulum stepping techniques, what they provide, and their advantages and disadvantages in conjunction with their associated control mechanism (e.g., how to steer or remain standing still). Figure 2 shows a comparison view of the most common pendulum-based techniques and control mechanisms.

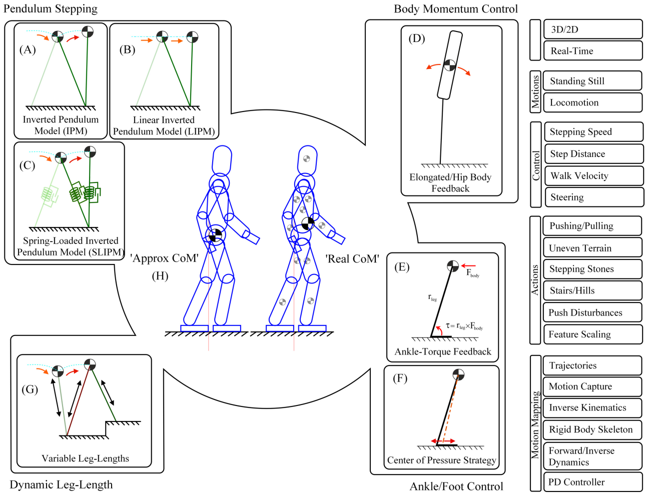

Figure 2: ***Stepping Model Components*** *- While there are different flavors and approaches for generating stepping motions based upon the pendulum model, we illustrate and compare the logic and features that each component provides. (A) The inverted pendulum model (IPM) was originally a biomechanically inspired approach [Vukobratovic 1972; Hemami 1977] that later gained recognition in robotics [Miura and Shimoyama 1984; Kajita and Tani 1995] and later the graphics community [KUDOH et al. 2006]. (B) Linear inverted pendulum model (LIPM) [Kajita et al. 2001]. (C) Spring-loaded inverted pendulum (SLIP) [Garofalo et al. 2012]. (D) Elongated-body (either for more life-like walking with upper body posture as shown by Kenwright [2011], or as a means of counter-balance correction [Pratt and Tedrake 2006]. (E) Ankle-Torque Feedback [Kenwright 2012]. (F) Center of Pressure Strategy [Pratt and Tedrake 2006]. (G) Variable leg-lengths [Pratt et al. 2006] with an IP model to compensate for push disturbances using the capture-point, while Ito and Sasaki [2011] performed lateral stepping based on zero moment point feedback for adaptation to slopes. (H) The hip midpoint as the COM position similar to SIMBICON [2007] due to it being fast and simple, however, the model could be adapted to constantly update and track the full articulated body COM position synonymous with the approach by Tsai et al. [2010].*

3 Pendulum Stepping Model

The biomechanically inspired inverted pendulum (IP) is at the **heart** of a number of character balancing models since it is an intuitive, computationally fast, algorithmically simple, and robust technique for providing dynamic, interactive, and controllable stepping information. The uncomplicated IP model is a point-mass supported by a single telescopic mass-less leg (as shown in Figure 2). While there are numerous extensions, for example, with double-support feet and multi-mass body parts, we focus primarily on the elementary model (e.g., single leg point-mass rigid/spring leg model).

The stepping motion of a rigid-leg pendulum model on flat ground under ideal situations can maintain a perpetual (i.e., constant) walking motion by converting energy between kinetic and potential energy (i.e., point mass continually pole-vaulting over the supporting leg). The basic pendulum stepping motion is **passive** by default; however, an **active** system allows us to add controlling feedback forces (and torques) into the stepping mechanism to gain greater control (e.g., speed and steering).

The low-dimensional IP model on its own has a number of limitations (e.g., pin-point feet and steering inability) and must be combined with a control mechanism (e.g., foot, hip, or ad-hoc feedback forces) to make the model a viable solution for generating controllable character-based motions. The stand-alone pendulum stepping model limitations are:

- Continual state of motion (i.e., always needs to keep stepping to remain upright and balanced)
- Pin-Point Feet (i.e., no support area or ankle torque)
- No feet or pelvis orientation information
- No postural information (i.e., upper body orientation)
- Mass-less legs
- No feet trajectory information (e.g., height, speed, direction)
- Requires multiple steps for steering (i.e., cannot start locomotion from a stop and needs to wait for gravity to pull it forwards which can be the wrong desired direction) - no steering control
- Does not account for double support foot placement (i.e., when both feet are on the ground supporting the body)
- No friction or ground-feet slipping

While there are different techniques for solving the simple analytical IP problem mechanics to accomplish specific goals (e.g., continual locomotive stepping), we use a "velocity-based" approach for solving the IP model's equations. We control the direction and speed of the pendulum-based model by means of different control mechanisms (i.e., variable leg-length and ankle-torque) to enable the user to vary the step position and duration while remaining balanced and upright. We then take the low-level stepping model information and map it onto an articulated character to create full-body coordinated motions.

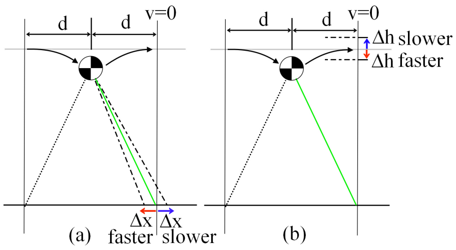

Figure 3: ***Capture-Point Comparison*** *- The capture-point concept for (a) capture-point "distance", and (b) capture-point "height".*

The model is made as simple as possible (i.e., a low-dimensional model) and gives us the following advantages:

- The balancing motion can be decoupled from the overall motion
- We can focus specifically on one crucial motion
- The full-body movement can be reconstructed around the simple model (we can take advantage of the redundancy as a secondary priority means of mixing in behavioral emotions, such as tired and happy)

3.1 Capture-Point

The capture-point defined by Pratt and Tedrake [2006] is a position on the ground that would bring the final pendulum model to a complete stop when vertically upright (i.e., final velocity equal to zero). We define this as a capture-point "distance", since it calculates the unknown step-distance based on a fixed length-leg approximation. However, we define a capture-point "height" based upon the same principle, however, step-distance is known and the final leg-length height is what we calculate. The reasoning behind this is that in complex virtual environments a character's stepping location can be limited or constrained (e.g., in stepping stones). For a pin-point rigid-leg pendulum model, we calculate the destination leg-length for the step transitions necessary based upon the foot placement distance that would result in the mass reaching a zero velocity when vertical. We illustrate the capture-point distance and capture-point height in Figure 3.

Capture-Point "Distance": The capture point "distance" is the specific foot position from the current projected location on the ground that will bring the pendulum to a stop (i.e., velocity will reach zero when the pendulum is standing vertically upright and straight), as shown in Figure 4. This method was proposed by Pratt and Tedrake [2006] who applied it to both a pendulum model (i.e., arc like trajectory) and linear-pendulum model (i.e., flat fixed height trajectory).

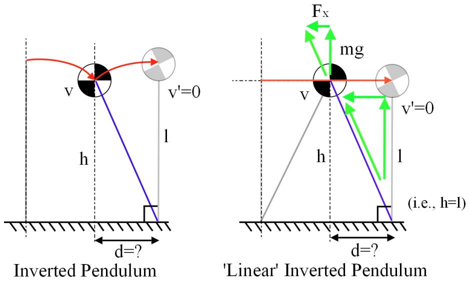

Figure 4: ***Capture-Point "Distance"*** *- Estimating the capture point "distance" based on a rigid mass-less support leg.*

Capture-Point "Height": In contrast to the capture-point "distance", which focused on finding the unknown stepping distance necessary to bring the pendulum mass to a vertical upright stop, the capture-point 'height' focusing on finding the final leg-height given a specific stepping distance to achieve the same task. *If we specify a specific foot placement location it means we can carefully control and navigate the pendulum stepping model in complex virtual environments.* However, the formula for calculating the leg-length is not as elegant and straightforward as the capture-point "distance" approach.

3.2 Control Mechanisms

The capture-point does not provide a means of 'control' and, hence, must be combined with an additional control mechanism (e.g., body-momentum or ankle-torque) so we can steer and guide the pendulum during foot transitions. The control mechanism keeps the pendulum balanced and allows us to direct the movement in a controlled manner. In summary, combining the IP model with a feedback control mechanism fixes a number of inherent oversimplification limitations to produce a viable practical solution that is robust and controllable.

The three fundamental control mechanisms we focus on are:

- Ankle-Torque Feedback (e.g., to avoid constant stepping, provide additional control, and static balancing data)
- Elongated-body (e.g., hip-joint torque, steering, and postural feedback information)
- Variable Leg-Lengths (e.g., walking up stairs and changing terrain heights)

Our approach exploited the ankle-torque control mechanism in conjunction with the capture-point height.

3.3 Mapping: Bridging the Gap between Control and Kinematics (IP to Full-Body)

We address the issue of mapping the low-dimensional model onto a fully articulated biped skeleton. There are a number of *unknowns* that must be addressed, such as foot and arm trajectories. The inverse kinematic (IK) solver maps a solution between our IP model and our highly articulated biped skeleton hierarchy. While the highly articulated skeleton contains a huge amount of flexibility and ambiguity (i.e., multiple solutions for achieving the same goal), in comparison to the simplified low-dimensional model which is minimalistic, computationally efficient, and straightforward to solve. The simplified model, however, possesses multiple attributes (i.e., overall center-of-mass position and feet locations) that are common to the highly articulated skeleton, which are fundamental for generating physically correct balanced biped stepping poses. To accomplish the mapping efficiently, we subdivided the IK problem into two separate parts (i.e., upper and lower body). This made solving the IK problem faster and more robust. Moreover, our adaptive stepping technique solves balancing logic while the upper-body motions are left free for alternative actions, such as personality and style (e.g., looking around, arms' swaying).

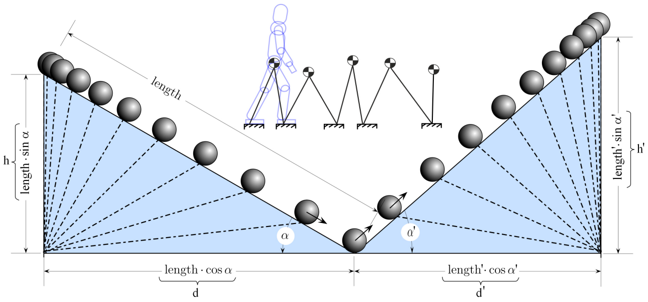

Figure 5: ***Capture-Point "Height"*** *- Estimating the capture point "height" based on a rigid mass-less support leg (illustrate a linear transition). The principle focuses on trading energy to increase or reduce momentum by means of increasing or decreasing the leg-length between foot placement transitions.*

We focused on lower body movements since they are the most crucial for upright balancing motions [Tsai et al. 2010] compared to the upper body. While, foot trajectories were generated by interpolated Bezier splines between the current and desired landing positions during foot transitions.

The final motions **did not** use any motion capture or key-framed libraries. Hence, some of the motions may have appeared to look a bit robotic. This approach can be remedied by combining the generated motions with a multiple priority IK solution (i.e., with a primary and secondary goal). Whereby, the primary balanced physically correct motions are always enforced, while the secondary less crucial aesthetically pleasing life-like motions are combined on top from sources, such as key-framed libraries or random motion generators.

4 Experimental Results

The flexible nature of our stepping model is shown in Figure 1 and Figure 6, which shows screen captures of our pendulum-based approach mapped onto a simple biped rig. The model performs a variety of controlled stepping motions under different conditions (e.g., slopes, stairs, pushes, and avoiding holes).

5 Conclusion

We have presented and demonstrated a novel stepping model based on the combination of different techniques (i.e., capture-point height and ankle-torque) that is flexible, robust, and computationally efficient. The final biped stepping motions remained balanced against perturbations, such as random sudden pushes, and generated movements similar to those observed in humans.

We generated the fundamental stepping actions without any motion capture data. The basic model for maintaining balance was based on a pendulum-based technique and required a minimum number of tunable parameters. While we explained and compared the different control mechanisms, we settled on the uncomplicated ankle-torque feedback mechanism in conjunction with a variable leg-length system. All in all, the generated low-dimensional model can be mapped onto a whole-body biped character to create common upright balanced stepping movements (e.g., walking and standing).

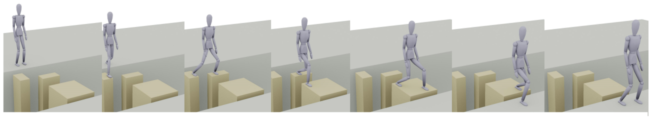

Figure 6: ***Controlled Stepping*** *- We carefully control the stepping locations of feet while navigating a complex environment (i.e., we cannot always place our feet at desired locations and must work within the constraints of the environment).*

References

GAROFALO, G., OTT, C., AND ALBU-SCHAFFER, A. 2012. Walking control of fully actuated robots based on the bipedal slip model. 2

HEMAMI, H. 1977. The inverted pendulum and biped stability. *MATHEMATICAL BIOSCIENCES 34, 95-110 (1977)*. 2

ITO, S., AND SASAKI, M. 2011. Motion control of biped lateral stepping based on zero moment point feedback for adaptation to slopes. *A.C. Pina Filho (Eds.), Biped Robots, Rijeka: InTech*, 15–34. 2

KAJITA, S., AND TANI, K. 1995. Experimental study of biped dynamic walking in the linear inverted pendulum mode. In *Robotics and Automation, 1995. Proceedings., 1995 IEEE International Conference on*, vol. 3, 2885 –2891 vol.3. 2

KAJITA, S., KANEHIRO, F., KANEKO, K., YOKOI, K., AND HIRUKAWA, H. 2001. The 3d linear inverted pendulum mode: a simple modeling for a biped walking pattern generation. In *Intelligent Robots and Systems, 2001. Proceedings. 2001 IEEE/RSJ International Conference on*, vol. 1, 239 –246 vol.1. 2

KENWRIGHT, B., DAVISON, R., AND MORGAN, G. 2011. Dynamic balancing and walking for real-time 3d characters. In *Proceedings of the 4th international conference on Motion in Games*, Springer-Verlag, Berlin, Heidelberg, MIG'11, 63–73. 2

KENWRIGHT, B. 2012. Responsive biped character stepping: When push comes to shove. In *Proceedings of the 2012 International Conference on Cyberworlds*, vol. 2012, 151–156. 2

KUDOH, S., KOMURA, T., AND IKEUCHI, K. 2006. Stepping motion for a human-like character to maintain balance against large perturbations. In *Proceedings of the 2006 IEEE International Conference on Robotics and Automation, Orlando, Florida*. 2

MIURA, H., AND SHIMOYAMA, I. 1984. Dynamic walk of a biped. *The International Journal of Robotics Research 3*, 2 (jun), 60–74. 2

PRATT, J., AND TEDRAKE, R. 2006. Velocity-based stability margins for fast bipedal walking. In *Fast Motions in Biomechanics and Robotics*, Springer Berlin Heidelberg, M. Diehl and K. Mombaur, Eds., vol. 340 of *Lecture Notes in Control and Information Sciences*, 299–324. 2, 3

PRATT, J., CARFF, J., AND DRAKUNOV, S. 2006. Capture point: A step toward humanoid push recovery. *Proc. Humanoid Robots*, 200–207. 2

TSAI, Y.-Y., LIN, W.-C., CHENG, K. B., LEE, J., AND LEE, T.-Y. 2010. Real-time physics-based 3d biped character animation using an inverted pendulum model. In *IEEE Transactions on Visualization and Computer Graphics*, vol. 16:2, 325–337. 2, 4

VUKOBRATOVIC, M. 1972. On the stability of anthropomorphic systems. *MATHEMATICAL BIOSCIENCES 15, 1-37*. 2

YIN, K., LOKEN, K., AND VAN DE PANNE, M. 2007. Simbicon: simple biped locomotion control. In *ACM SIGGRAPH 2007 papers*, ACM, New York, NY, USA, SIGGRAPH '07. 2