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Modeling Ascending and Descending Stairs Using the Human Motion Simulation Framework

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ABSTRACT

The Human Motion Simulation Framework (Framework) is a hierarchical set of algorithms for predicting and analyzing task-oriented human motion. The Framework was developed to improve the performance of commercial human modeling software by increasing the accuracy of predicted motions and the speed of generating simulations. This paper presents the addition of stair ascending and descending to the Transition Stepping and Timing (Transit) model, a component of the Framework that predicts gait and acyclic stepping.

INTRODUCTION

One of the most important impediments to the wider use of digital human figure models for ergonomic analysis is the time-consuming nature of posture and motion simulation using current tools. Several systems have been proposed for organizing task specification in a manner that will allow the software to automatically generate a predicted motion without manual posturing of the figure. The Task Simulation Builder (TSB) developed for the Jack software provides a structure for specifying task elements independent of the current state of the environment and manikin (Raschke et al. 2005). TSB builds on the concepts embodied in the Parameterized Action Representation (Badler et al. 2005).

The Human Motion Simulation Framework (Framework) was developed at the University of Michigan to provide a structure for organizing the algorithms, software, and research addressing the problem of task-oriented human simulation (Reed et al. 2006). The Framework algorithms are independent of any particular human simulation software, but have been demonstrated using a Reference Implementation written for the Jack human model. The Framework has been applied to simulation of wide range of tasks, with unique applications to acyclic transition stepping (Wagner et al. 2005, Reed and Wagner 2007), force-exertion postures (Hoffman et al. 2008), and vehicle ingress and egress (Reed and Huang, 2008). The current work was conducted using the Reference Implementation of the Framework in the Jack 6.0 digital human modeling environment from Siemens.

Efficient generation of simulations for ergonomic analysis is aided when the software user is able to specify tasks to the software at the same high lexical level at which a worker would be instructed. Badler et al. (2005) devoted considerable research to the specification of a natural language interface for instructing avatars, with applications to real-time distributed simulations. The success of these approaches requires that the software be able to decompose a "high level" directive into the individual elements by which the specified task can be performed in the current context by the simulated human. As a simple example, a simulated industrial worker instructed to place object A at location B on assembly C would need to (1) determine the location of object A, (2) walk or otherwise obtain a position necessary to pick up object A, carry object A to the site of assembly C, and (3) place the object. A large variety of complicating factors that the software may need to consider can be imagined, such as obstacles in a desired walk path, complex object

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grasp requirements, and adverse environmental conditions such as cold or poor lighting.

Aside from the challenges of developing movement planning algorithms that can address these issues, the algorithms must obtain sufficient information from the simulation to perform realistically, for example determining which objects in the scene may not be contacted and which are potential supporting surfaces. Thus, the user interface for annotating objects in the environment and the manikin itself (age, muscle strength, training level, etc.) becomes a critical consideration in the development of motion simulation methods. What information can the developers of simulation algorithms reasonably expect to have available, and what is the most efficient means for the user to provide or the software to obtain that information?

The efficiency of simulating locomotion is one important consideration for human modeling system design. Because both cyclic gait and acyclic stepping are common components of goal-oriented human tasks, the software should provide an efficient interface for defining tasks in such a way that required walking or stepping can be inferred by the software. Part of that process is the identification of geometric components in the scene that represent surfaces that can be walked on, including stairs and other constructions used to by workers change their elevation.

This paper presents an implementation of stair traversal in the Framework as an extension of the Transition Stepping and Timing (Transit) model (Reed and Wagner, 2007). The Transit model defines stepping for purposes of human motion simulation as a timed sequence of foot placements, with cyclic gait as a particular case with symmetric and repetitive foot placements. The Transit model defines transition tasks in the context of task-oriented behavior such as picking up or placing objects. Because locomotion is assumed to be an activity supporting other activities rather than a goal in itself, the planning of locomotion is based on the identification of transitions (often changes of direction or load) associated with picking up and placing objects or otherwise interacting with the environment through the upper extremities or gaze.

METHODS

OVERVIEW OF APPROACH – A generic software representation of stairs was developed as extension of the transition stepping task introduced by Reed and Wagner (2007). The user defines a "stairs" object in the environment (see below) and this object is passed as a walk target to the Jack manikin enhanced with HUMOSIM functionality. The simulated human navigates the flight of stairs by computing foot and pelvis trajectories based on body dimensions and stair features such as inclination angle and step offset.

STAIRS AS TRANSITION TASKS –The Transit model introduced the concept of a transition behavior that represents the pattern of foot placements (or, equivalently, discrete movements) during an interaction with the environment using one or both upper extremities. Wagner (2008) developed an Integrated Stepping Model (ISM) that computes the step placement and timing for a sequence of transitions, potentially connected by cyclic gait strides. The HUMOSIM Framework includes an implementation of the ISM that allows the user to specify a sequence of walk targets defined by locations or by objects to be manipulated or picked up. Using Wagner's Transit model, the ISM in the Framework computes the step placement and timing to move the manikin through the sequence of transitions, including any intervening cyclic gait.

Following the L-TRACS model described in Wagner et al. (2008), the Framework computes approach and departure steps for each transition. One set of departure steps is computed with the number of steps and their positions and orientation determined by the direction of the subsequent transition. Two sets of approach steps are computed, one beginning with the right foot and one with the left. As the ISM puts together the transitions in sequence, the set of approach steps that fits best with the approaching gait strides (or the departure from the previous transition) is selected as described in Wagner (2008).

In principle, this approach can be used with an approach step sequence that is arbitrarily long, rather than the two- and three-step approaches specified in the Transit model for object transfer tasks. Consequently, the pattern of steps associated with ascending or descending stairs fits easily into the ISM by considering the sequence of steps on the stairs as an "approach" to the terminal position at the top or bottom.

DEFINING STAIRS **–** Scenes that contain stairs will typically be complex, and the surfaces defining the steps will often be integrated into other objects. Consequently, selecting individual graphical elements to define as steps in a flight of stairs or the surface of a will often be problematic. A preferable approach is for the user to define the stairs by specifying a top and bottom location and number of steps. A user interface has been developed that flexibly allows the user to define any sufficient combination of starting and ending location, and, for stairs, the number of steps or horizontal and vertical offsets (depth and rise). This approach makes it easy to mark up an existing scene. Schematic geometry is automatically created to verify that the locations are accurately defined. Irregular stair layouts can be defined by manually relocating the schematic step geometry. Stairs created in this way can be passed to the Framework as walk targets, interspersed with other targets as desired.

COMPUTING FOOT PLACEMENTS – Foot placements on stairs are computed based on the results of an analysis of video data from a small number of subjects. For typical stair configurations, people place about ¾ of the length of the foot on the step when ascending. When descending, the foot (shoe) is placed to locate the ball of the foot on the step, with part of the distal portion of the foot extending beyond the edge of the step for people with relatively long feet.

For simulations, right and left foot placements are computed for each step and interlaced to create two alternating left-right patterns starting on each foot. The direction of traversal is determined by the elevation of the figure at the time the transition task is dispatched. If the figure elevation is closer to the bottom than the top, the figure will enter the stairs at the bottom, and vice versa. This allows the same transition task to be used repeatedly to simulate ascending and descending the same flight of stairs without the requirement for the software user to specify the direction.

TAILORING FOOT TRAJECTORIES – The Framework parameterizes stepping in terms of targets for the feet, along with their associated timing (see Reed and Wagner, 2007). At run time, when a step task with an associated target is dispatched to a lower extremity component (right or left), the component computes a trajectory from the current location to the target. Trajectories in the Framework are parameterized using third-order Bézier curves, which provide control over the approach and departure gradients (Faraway et al. 2007). When the step targets for stair negotiation are generated, they are assigned an associated motion type value. The motion type is interpreted in the lower extremity component of the Framework to determine how to set the Bezier control points to produce the desired foot trajectory.

The foot trajectory is controlled to avoid colliding with the steps. The interior control points of the Bézier curve are located using simple linear relationships that depend on the stair geometry (rise and depth) so that the trajectories are automatically adjusted based on stair layout.

WHOLE-BODY MOTION – As described in Reed and Wagner (2007), the Framework generates whole-body stepping motions (including gait) using the predicted foot placements and their timing as input. Pelvis targets are computed from foot placements using empirical findings from motion-capture studies of gait and acyclic stepping (Reed and Wagner 2007). Figure 1 shows a schematic of the prediction process. The component modules are described in more detail in Reed et al. (2006). The lower-extremity and pelvis components compute trajectories as each step or new pelvis target is dispatched, based on the current state of the manikin. Limb and torso motions are computed using behavior-based models based on analytical inverse kinematics.

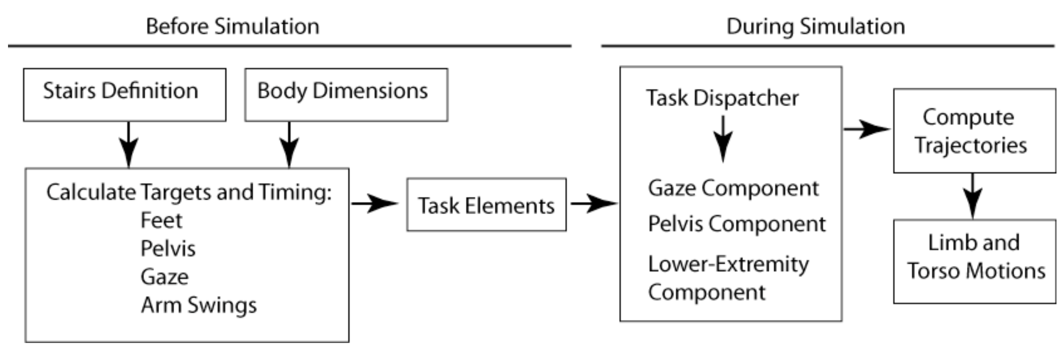

Figure 1. Schematic of prediction process.

RESULTS

Figures 2A and 2B show frames from simulations of stair ascending and descending with two different step layouts. For clarity, only a small number of steps are shown, but the algorithm works equally well with an arbitrary number of steps. The figure shows the foot placements relative to the steps, which are set automatically. The foot placement respects the step offset, which is a key consideration to avoid collision during foot motions. Arm swings are automatically generated, although they can be overridden by other upper-extremity tasks, such as carrying an object. Spine motions associated with ambulation are automatically generated based on the pelvis motions. Automatic gaze control directs the vision toward the steps for initial path planning, then toward the continuing walk path as the end of the flight of steps is approached. Gaze targets can also be overridden to simulate closer monitoring of the steps, for example.

Figure 2A. Frames from a simulation of ascending a set of stairs. Foot placements are shown in red.

Figure 2B. Frames from a simulation of descending a set of stairs. Foot placements are shown in red

DISCUSSION

This paper presents a kinematic approach to the simulation of stair climbing and descent that is integrated within a general-purpose human motion simulation structure. The methodology is a straightforward extension of the motion-parameterization methods that have previously been applied to acyclic stepping (Reed and Wagner 2007) and vehicle ingress and egress (Reed and Huang 2008). This close integration ensures that stair traversal can be included easily in task simulations that include other walking, acyclic stepping, and upper-body tasks. Stairs are represented by a software abstraction that allows users to define stair steps within an environment without requiring isolated geometric elements to be identified.

The most similar previous effort was reported by Bhatt et al. (2008), who used multi-objective optimization to predict the lower extremity motions associated with stair ascent. An important advantage of the Bhatt et al. approach is that the results are dynamically consistent, given the linkage definitions including segment mass and inertia parameters. The dynamic approach allows changes in the figure task, such as adding a heavy backpack, to be handled automatically, although the results are not necessarily similar to typical human behavior. The current kinematic approach is much simpler computationally and is well integrated into a general-purpose task simulation framework, but similarly does not guarantee realism. Results from the behavioral studies of task performance that would be needed to tune and validate the dynamic simulation approach can also be readily implemented in the HUMOSIM

Framework to improve the accuracy of the kinematic simulation (Reed and Huang 2008). The current emphasis on the simplicity and efficiency of the simulation is justified when stair traversal is primarily of interest for visualization rather than analysis, which is typically the case in industrial ergonomics. Nonetheless, a keyframe-based animation technique would be inadequate because of the need to programmatically switch among different size manikins, change the number of steps, or alter the workplace layout. All of these changes can be made simply with the current approach, often without alternation the task specification at all. In contrast, an animation-based approach would require extensive regeneration of postures if the layout were changed.

Further work is needed to improve the current simulation capability. The implementation described here does not provide a simple interface for handing uneven steps or changes in orientation within a flight of stairs, although no major changes in the algorithm would be needed. The use of handrails is not yet simulated in an automated fashion. Most importantly, motion-capture data from subjects with a range of physical dimensions and capabilities would provide the opportunity to improve validity of the simulation.

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