May 1993

Intermittent Non-Rhythmic Human Stepping and Locomotion

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University of Pennsylvania Department of Computer and Information Science Technical Report No. MS-CIS-93-55.

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Abstract

When humans need to get from one location to another, there are many occasions where non-rhythmic stepping (NRS) is more desirable than normal walking. This can be observed in performing tasks in a constricted work space. For this purpose NRS is considered as a variation of curved path walking. Four types of local adjustment are dealt with: forward, backward, lateral stepping, and turnaround. Combined with curved path walking, NRS provides a very useful tool for animating human locomotion behaviors. In the lower body motion, the trajectory of the hip, angular trajectory of the feet, and the trajectory of the swing ankle during the swing phase determine the basic outline of an NRS. These trajectories are precomputed at the start of each step. The stepping process is called with a *normalized time* to generate the actual pose of the NRS at that moment. the normalized time is a logical time, covering zero to one during a complete step.

Keywords

animation, human locomotion, non-rhythmic stepping, trajectory

Comments

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MS-CIS-93-55
GRAPHICS LAB 56

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INTERMITTENT NON-RHYTHMIC HUMAN STEPPING AND LOCOMOTION

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Abstract

When humans need to get from one location to another, there are many occasions where non-rhythmic stepping (NRS) is more desirable than normal walking. This can be observed in performing tasks in a constricted work space. For this purpose NRS is considered as a variation of curved path walking. Four types of local adjustment are dealt with: forward, backward, lateral stepping, and turnaround. Combined with curved path walking, NRS provides a very useful tool for animating human locomotion behaviors. In the lower body motion, the trajectory of the hip, angular trajectory of the feet, and the trajectory of the swing ankle during the swing phase determine the basic outline of an NRS. These trajectories are precomputed at the start of each step. The stepping process is called with a *normalized time* to generate the actual pose of the NRS at that moment. The normalized time is a logical time, covering zero to one during a complete step.
Keywords: animation, human locomotion, non-rhythmic stepping, trajectory

1 Introduction

Human locomotion occupies a large part of human activities. The correct simulation of linear path locomotion (LPL), the simplest form of human locomotion, is already a difficult problem. Many groups have been interested in extracting generic facts of [6,11,12], measuring [17,18], simulating [16] human walking, or even making a robot that takes steps [7,15].

Bruderlin and Calvert built a keyframeless locomotion system for straight walking paths [3,4]. They generated every single frame based on both dynamics and kinematics. Walking was controlled by three primary parameters: step length, step frequency, and velocity. Various walking styles could be produced by changing the walking attributes.

Boulic *et al.* tried a generalization of experimental data based on the normalized velocity of walking [2]. They put a correction phase (inverse kinematics) to handle the possible constraint violation of the computed values. In that process they introduced the *coach concept*, which basically chooses among the multiple inverse kinematic solutions one that is the closest to the original motion.

We [9] developed a technique that generalizes walking motion data collected from measurements of a particular subject so that it can be applied to figures of different proportions and sizes, and/or different step lengths. The quality of the generalization is measured by its ability to preserve the original characteristics of the measured walk.

Curved path locomotion (CPL) is a natural extension of LPL, since the human walking path must be frequently a curve. We attempted a further generalization from LPL to CPL [1,8]. In building a CPL system, we tried to utilize pre-existing LPL systems. That is, an LPL system is used as a subsystem to the CPL system. Our generalization algorithm from LPL to CPL was based on the intuition that there should be a smooth transition between linear and curved path locomotion: if the curvature is not large, the curved path walking generated by our CPL system should be close to the linear path walking given by the underlying LPL system. In particular, if the given curve is actually a straight line, the resulting CPL should match that of the underlying LPL system. No assumptions were made about the underlying LPL system, therefore most LPL systems can be generalized into CPL ones by our algorithm. Clearly the underlying LPL will determine the stylistics of the resulting CPL. The algorithm adds a small constant cost ($O(1)$) to any pre-existing LPL algorithm.

Even though normal walking (rhythmic walking such as CPL) is used for a long distance location change, there are many occasions where some non-rhythmic stepping is required to adjust the position of the body locally. Frequently, people move within a narrow space, back and forth, taking one or two steps intermittently, which is somewhat different from walking. For example, suppose a hammer is located on a table and should be placed on another table which is just one or two steps away. In this case *non-rhythmic stepping* (NRS) would be more appropriate than normal walking for the locomotion.

The problem of simulating NRS has not yet been tackled significantly. Phillips and Badler tried an interactive generation of stepping behaviors that keep the static balance (no inertia terms) [1,13,14]. Application of full dynamics requires the prediction of active internal torques at the joints during the NRS motion, which is difficult when the kinematics of the motion is not known (problem of too many unknowns). This introduces the control problem, which is not easy, especially when a certain realism is required. Thus a conventional dynamics technique does not give a solution for this NRS problem. In this paper we propose a solution based on a kinematic generalization.

NRS motion tends to be more irregular than normal walking. In its direction, it can be *backward* or *lateral* as well as *forward*. For a drastic directional change, *turning around* (on a pivot leg) would be effective. We will consider these four forms of NRS in this paper. Among them, the forward, backward, or lateral stepping will be treated as a group, denoted by NRS^-. (Even though hopping is also non-rhythmic, we do not consider it as a form of NRS in this paper; we assume at least one of the feet stays on the ground all the time.)

Some terminology will be defined in the next section. The overview of NRS generation will be shown in Section 3. The input parameters that controls the motion of NRS are listed in Section 4. The details of NRS^- and turnaround will be explained in Section 5 and Section 6, respectively.

2 Definitions

At a certain moment, if a leg is between its own heelstrike (beginning) and the other leg's heelstrike (ending), it is called the *stance leg*; otherwise it is called the *swing leg*. For example, in Figure 1, the left leg is the stance leg during interval 1, and the right leg is the stance leg during interval 2. Thus at each moment we can refer to a specific leg by either stance or swing leg with no ambiguity. The joints and segments in a leg will be referred to using prefixes *swing* or *stance*. For example, swing ankle is the ankle in the swing leg. (In the literature, the stance and the swing phases are longer and shorter than the step duration, respectively. Our definition of the prefixes *stance* and *swing* is solely for clear designation of the legs at any moment.)

Let HSM^- be the Heel Strike Moment just before the current step, HSM^+ be the Heel Strike Moment right after the current step, which is one step after HSM^-, FGM be the moment when the stance foot gets to be flat on the ground (Flat Ground Moment) after HSM^-, MOM be the Meta Off Moment [3,4] when the toes begin to rotate around the tip of the toe, and TOM be the Toe Off Moment.

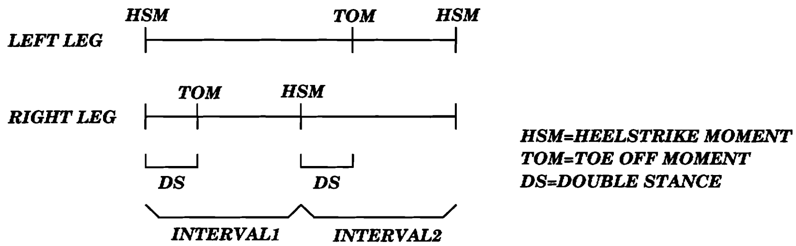

Figure 1: The Phase Diagram of Human Locomotion

3 Overview of NRS Generation

There are four primitives for NRS generation: **INITIALIZE_NRS$^-$(walker,** *specs*, **step_duration)** and **ADVANCE_NRS$^-$(walker, normalized_time)** for NRS$^-$, and **INITIALIZE_TURNAROUND(walker,** *specs$'$*, **step_duration)** and **ADVANCE_TURNAROUND(walker,normalized_time)** for the turnaround. Both **INITIALIZE_NRS$^-$** and **INITIALIZE_TURNAROUND** will be collectively called **INITIALIZE_NRS**. Similarly both **ADVANCE_NRS$^-$** and **ADVANCE_TURNAROUND** will be called **ADVANCE_NRS**.

Each NRS$^-$ or turnaround is initialized by **INITIALIZE_NRS**, which precomputes the higher level part so that **ADVANCE_NRS** can be handled in $O(1)$ time later. In **INITIALIZE_NRS, walker** specifies the walker to be initialized for the NRS. This way there can be multiple walkers in the same scene. *specs* and *specs$'$* are the input parameters that specifies the details of an NRS$^-$ and a turnaround, respectively, which will be the subject of the next section. The duration of the step is given by **step_duration**.

ADVANCE_NRS generates the walking poses of **walker** at the given **normalized_time. normalized_time** is the *logical* time: **ADVANCE_NRS(walker,0.0)** gives the pose at the beginning of the current NRS and **ADVANCE_NRS(walker, 1.0)** gives the pose at the end of the current NRS. By increasing **normalized_time** from zero to one, the stepping motion of a whole NRS can be generated. The step size Δt of **normalized_time** can be adjusted. It is a very effective way to adapt to the various machine speeds for realtime interactive NRS display. The concept of normalized time proved to be intuitive and easy to use for the animators.

The initializing primitives above precompute the trajectories of the ankles and the *center site* (the mid-point of the two hip joints) during the NRS. On each call of **ADVANCE_NRS** at the normalized time t, the locations of the center site, the stance ankle, and the swing ankle are looked up on the trajectories that have been computed in **INITIALIZE_NRS**. The center site location and its orientation determine the locations of the hips. The hip and ankle locations determine the configurations of the legs. The torso and the neck are twisted for an appropriate eye gaze direction.

The topmost level specification of an NRS is dealt with in Section 4. Sections 5

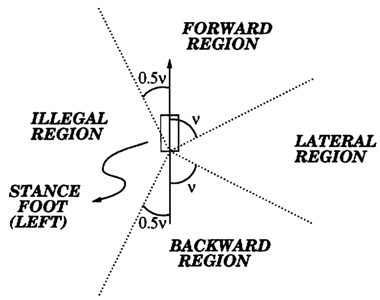

Figure 2: The Four Regions that Determine the Type of an NRS$^-$

and 6 describes the details of generating NRS$^-$ and turnaround, respectively.

4 Input Specification of NRS

There are many possible ways of generating an NRS. People show different motion styles in stepping the same NRS. Even the same person can step a given NRS in many different ways. Therefore we may need many parameters to control the outcome of the motion. Classification of the parameters into two categories, namely *goal parameters* and *attribute parameters*, enables a clear specification. Goal parameters specify the goal of the NRS. Attribute parameters describe *how* the goal is achieved.

We use the following six-tuple, *specs*, to describe an NRS$^-$.

$$specs = (\vec{footpos}, \vec{footdir}, left\_or\_right, swhf, \vec{eye\_gaze\_dir}, \vec{\theta}_{foot}) \tag{1}$$

$\vec{footpos}$ and $\vec{footdir}$ are the goal position and direction of the stepping foot. *left_or_right* is *left* when the stepping leg is the left one and *right* otherwise. These three parameters $specs_1 = (\vec{footpos}, \vec{footdir}, left\_or\_right)$ in *specs* are the goal parameters, and without them stepping cannot be shaped. There are various ways to achieve the step specified by $specs_1$, since there is no specific imposed pattern, as in normal walking. For example, the trajectory of the stepping foot can be higher or lower, without affecting the realism of the resulting motion.

To fix the details, we use three attribute parameters $specs_2 = (swhf, \vec{eye\_gaze\_dir}, \vec{\theta}_{foot})$. These parameters can be extended later to include other details. The swing height factor *swhf* tells how high the swing foot trajectory should be compared with $5cm$. If *swhf* is 1, then the maximum height component of the stepping is $5cm$, and the curvature is kept small during the swing. If it is zero, the foot is dragged. It can be over one for a high swing. $\vec{eye\_gaze\_dir}$ is the direction of eye contact at the end of the NRS. $\vec{\theta}_{foot}$ is used to specify the foot angles during the NRS. It will be explained in Subsection 5.1

Note that NRS$^-$ has three types: forward, backward, and lateral. The type is automatically determined from the current stance foot position and direction, and $\vec{footpos}$, as shown in Figure 2. The four regions, forward, lateral, backward, and

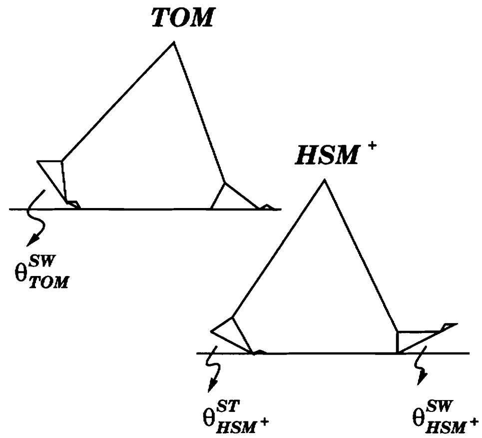

Figure 3: The Specification of the Foot Angles $\vec{\theta}_{foot}$ in an NRS$^-$

illegal, are defined by the four lines crossing at the stance heel position, and making the angles ν (constant) in the *favored* side, and 0.5ν in the *unfavored* side, with the direction of the stance foot. Depending on where $\vec{footpos}$ falls, we determine the stepping type. At the boundaries, $\vec{footdir}$ also counts. If it is almost parallel to the stance foot direction, the step is regarded as a lateral step; otherwise it is regarded as either a forward or a backward step. In our implementation, ν is set to 60 degrees.

For turnaround, we need a different specification

$$specs' = (angle, left\_or\_right, type) \tag{2}$$

where *angle* is the amount of turn in degrees, and *left_or_right* is the direction of the turnaround. These two are the goal parameters. The attribute parameter *type* will be explained in Section 6. Turnaround takes two steps: the first one makes the body twisted by the *angle*, and the next one recovers the normal stance. If *left_or_right* is *left*, it takes the left step first to turn the specified angle to the left, with the right foot fixed. Then the left foot is fixed to take the right step for recovering the normal stance. The case when *left_or_right* is *right* is similar.

5 NRS$^-$

In this section we show how an NRS$^-$ described by *specs* is generated. Subsections 1 through 3 show how the three basic trajectories (the ankles and center site) are formed in **INITIALIZE_NRS$^-$**. Subsection 4 shows how it can generate the pose at normalized time t through **ADVANCE_NRS$^-$**. Within this section, we may use NRS for NRS$^-$, for notational simplicity.

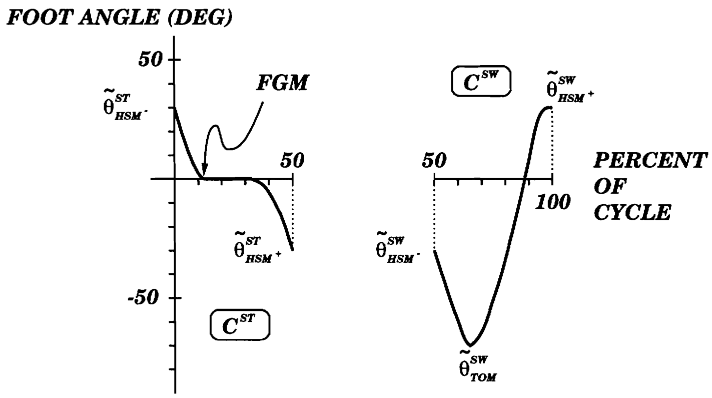

Figure 4: The Foot Angle Pattern during a Walking Step

5.1 Foot Angles

The foot angle over time in an NRS$^-$ does not follow the pattern of a normal step. Moreover, people show many different foot angle patterns in stepping the same step. Therefore the foot angle is included as an attribute parameter of NRS$^-$.

Among the control parameters of the foot angle trajectory, the final swing and stance foot angles (θ^{SW}_{HSM+} and θ^{ST}_{HSM+} in Figure 3) might be most decisive: they determine how the foot configurations end up after the NRS. However, the swing foot angle θ^{SW}_{TOM} at TOM also determines a part of the stepping pattern: the critical flexion of the foot just before its decrease. A big θ^{SW}_{TOM} in a small step, or vice versa may make the resulting motion look awkward. Thus the above three parameters $\vec{\theta}_{foot} = (\theta^{ST}_{HSM+}, \theta^{SW}_{HSM+}, \theta^{SW}_{TOM},)$ are used for foot angle trajectory specification.

Let's look at the pattern of the foot angles in human walking. According to Inman's study [6], they follow the pattern shown in Figure 4. The first piece C^{ST} in the figure is for the stance foot, and the second one C^{SW} is for the swing foot. The foot angles of NRS are obtained through the piecewise scaling of these curves, that makes the resulting curve satisfy the three control parameters above.

5.2 The Swing Ankle Trajectory

The height component of the swing ankle trajectory is approximated by a hyperbolic function, which is known for its small curvature:

$$f(t) = \frac{5 \times swhf}{e^{\frac{1}{2}} + e^{-\frac{1}{2}} - 2}(e^{\frac{1}{2}} + e^{-\frac{1}{2}} - e^{t-\frac{1}{2}} - e^{-t+\frac{1}{2}}) \tag{3}$$

where $0 < t < 1$.

The planar trajectory of the swing ankle is approximated by a straight line when there is no collision between the legs. If there is a collision with the straight line approximation, the path is approximated by a de Casteljau curve [5] with the three control points D_1, D_2, and D_3. D_1 is the starting point, D_3 is the ending point. D_2 is

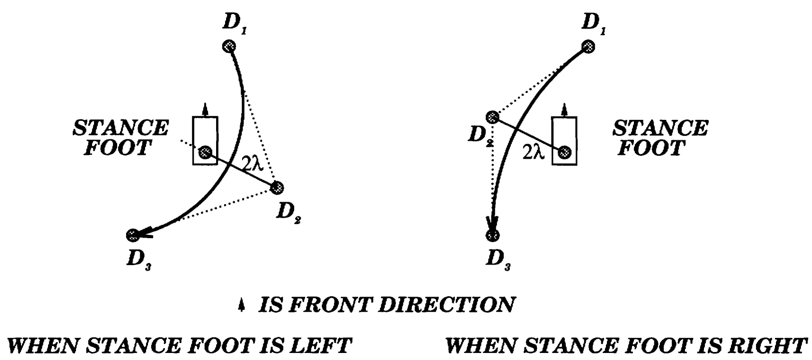

Figure 5: Control Point D_2 of the Swing Ankle Trajectory in a Backward Step

the point which is displaced from the stance ankle by 2λ in the perpendicular direction of $\vec{D_1 D_3}$ as shown in Figure 5. Here 2λ is the pelvis width. The displacement is on the left side if the stance foot is the right foot, and vice versa. The directional change of the swing foot during the stepping is obtained by interpolating the initial direction and the final one.

5.3 Center Site Trajectory

The planar center site trajectory is a straightforward approximation by a line segment. According to the stepping type, however, the height component of the center site trajectory varies. In lateral stepping, the center site height trajectories are different between the cases when the two feet become closer and farther apart. The hip height monotonically increases in the first case, and decreases in the second case. The height in lateral stepping is obtained by simulating an inverted pendulum.

In forward and backward stepping, we use the similarity with a curved path walking step. We compute the center site height trajectory $\{(t_i, h_i) \mid i = 1, \ldots, n\}$ of the underlying walking step of the NRS, at time t_i's (Figure 6). Given the foot angles in Subsection 5.1, we can compute the location of the ankles at HSM^+ of the NRS. Assuming that the knee flexions of the NRS and the underlying walking step are the same at HSM^+ (or it can be specified), we can compute the hip heights $h_{NRS}^{HSM^+}$ of the NRS at that moment. The hip height $h_{NRS}^{HSM^-}$ at HSM^- is given in the posture just before the NRS. Finally, the center site height trajectory $\{(t_i, h_i^{'}) \mid i = 1, \ldots, n\}$ of the NRS is obtained by the interpolation

$$h_i^{'} = h_i + (1 - t_i)(h_{NRS}^{HSM^-} - h_1) + t_i(h_{NRS}^{HSM^+} - h_n) \tag{4}$$

This interpolation tries to imitate the underlying curved path walking step, while satisfying the initial and final conditions.

Human locomotion study has focused on the rhythmic walking, mostly on straight forward walking. We are looking for a simple algorithm that can handle the backward steps as well. As the accompanying animation demonstrates, we can observe a visually

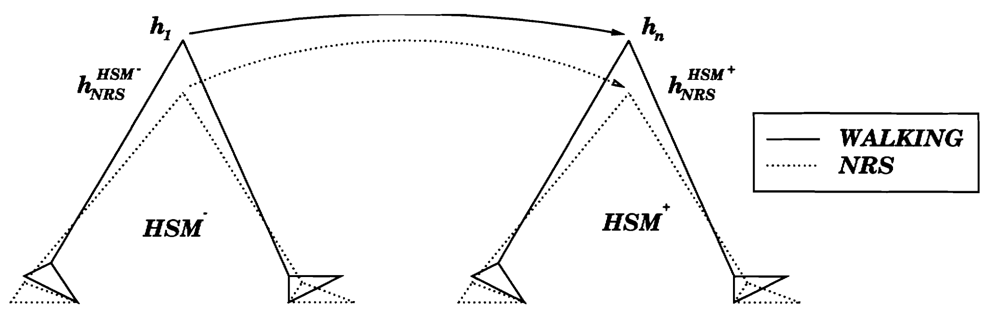

Figure 6: Computation of Hip Height Trajectory of a Forward NRS

acceptable backward walking by playing the forward walking animation in reverse. It suggests the idea of using the forward step to get the center site height trajectory of a backward step. The underlying walking step is the forward step which is the reverse of the backward NRS step that is being considered. The interpolation is given by

$$h_i' = h_{n-i+1} + (1 - t_i)(h_{NRS}^{HSM^-} - h_n) + t_i(h_{NRS}^{HSM^+} - h_1) \quad (5)$$

5.4 Lower Level Details

For each normalized time t, **ADVANCE_NRS$^-$** is called to generate the pose of the NRS. From the center site trajectory in the previous section we can locate the center site.

The facing direction of the pelvis at the end of the NRS is given by 0.5α, where α is the angle between the *lateral* direction and the line between the stance foot and $\vec{footpos}$ (Figure 7). The lateral direction here is determined by the direction of the stance foot.

Thus the orientation of the center site is obtained by interpolating the initial and the final directions of the pelvis. With the position and direction of the center site, the hip positions are easily computed. The foot angle trajectory and the swing ankle trajectory determine both foot configurations. Thus the ankle positions are known. Because the lengths of the thigh and the calf are constants, the leg configurations are fixed.

The eye gaze direction at time t is given as an interpolation between the initial facing direction and $\vec{eye\_gaze\_dir}$. Now, the angle of the eye gaze direction relative to the pelvis (facing) direction can be computed, which should be twisted along the torso and the neck. In our implementation, $\frac{2}{3}$ of the twist is done at the neck. The remaining $\frac{1}{3}$ is evenly distributed through the whole torso. The torso is modeled by 17 segments [10] in our implementation. Thus each vertebra is twisted by $\frac{1}{3} \times \frac{1}{17}$ of the total twist.

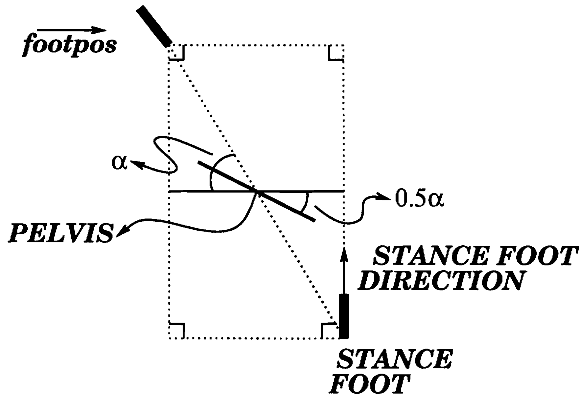

Figure 7: The Pelvis Direction at the End of an NRS$^-$

6 Turning Around

In a turnaround, the hip is monotonically lowered during the first step because the body is twisted, and then elevated in the recovering step. The directional change of the pelvis in turnaround is done by interpolating the initial direction and the final one. The swing ankle trajectory is obtained by treating the turnaround steps as forward steps. The foot angle is maintained at zero during this motion.

The turn angle is limited to 100 degrees at a time, since turn angles larger than 100 degrees gradually tend to produce non-realistic results in our implementation. If skidding is not permitted, it is close to the actual limit in human turnaround. If more than 100 degrees need to be turned, turnaround is used repeatedly. Turnaround takes two steps to complete the motion. There are many ways to take these two steps. For example, in turning left, the left step can be done first and then the right step can follow, or vice versa. But because the first case can be done with less lower body twist than the latter one, we use that convention.

A turnaround takes the two steps as follows: If the turnaround is a left turn, by the first step the left foot is put at 2λ back and left of the right foot, facing the goal direction. In the next step the right foot is located 2λ front and right of the resulting left foot, facing the goal direction. Putting the second stepping foot 2λ ahead facilitates the walking step that may follow. This turnaround is the *dynamic* type. Instead, by putting the second stepping foot side by side with the other foot, another turnaround can follow or the agent can continue a stationary task like grasping. This is the *stationary* type. This type is the attribute parameter of the turnaround as mentioned in Section 4. The case of the right turn is similarly determined. Figure 8 shows two examples: 90 degree left and right turnarounds (dynamic type). F_1^L, F_1^R are the initial left and right feet, and F_2^L, F_2^R are the ones after the turnaround. Note that the original positions F_1^L and F_1^R are not important in determining later foot positions in the left and the right turnarounds, respectively.

For realistic motion, eye gaze direction is put one half step ahead (Figure 9).

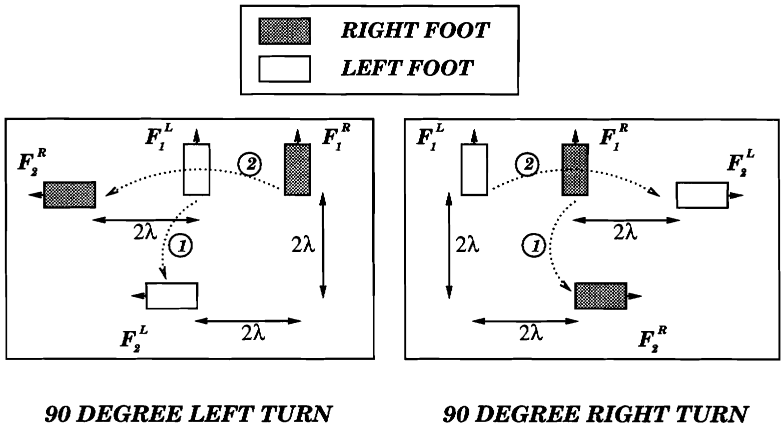

Figure 8: Foot Placements in 90 Degrees Left and Right Turnarounds

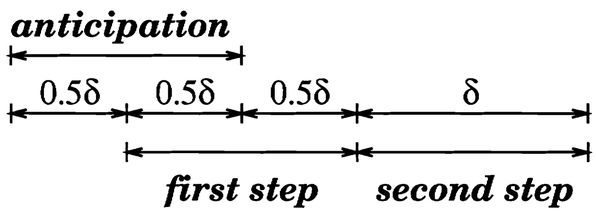

Figure 9: The Timing of the Anticipation in a Turnaround

Suppose δ is the duration of the first step of a turnaround. The torso and head begin to rotate to the goal direction 0.5δ before the first step begins. During the first δ, the gaze direction changes from the initial direction to the goal direction. Therefore the anticipation and the first step overlap during 0.5δ, and the total time taken for a turnaround is 2.5δ. Once the eye gaze direction is determined by an interpolation at each time step, the torso and neck are twisted as in Subsection 5.4.

7 Implementation and Conclusion

The four types of NRS are implemented in *Jack*™ [14]. Snapshots during a forward, backward, lateral steps, and turnaround are shown in Figures 10, 11, 12, and 13, respectively. Combined with curved path locomotion, NRS has proved to be very useful in animating the general human behaviors where small steps are needed occasionally in a constricted space. The resulting motion turns out to be reasonably realistic.

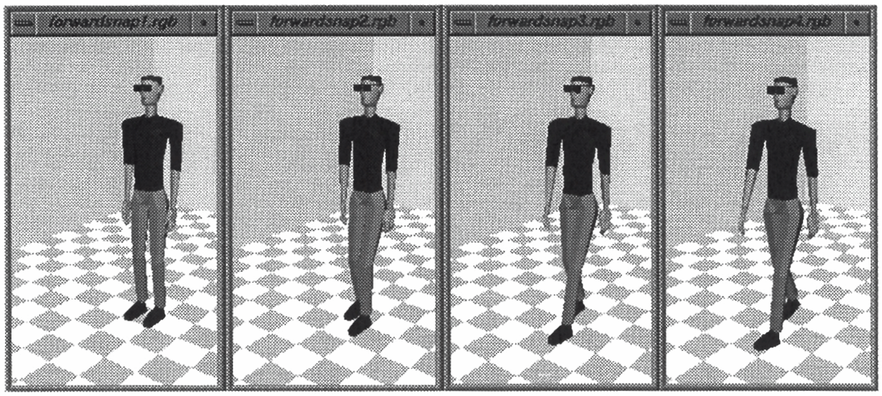

Figure 10: The Four Snapshots during a Forward Step

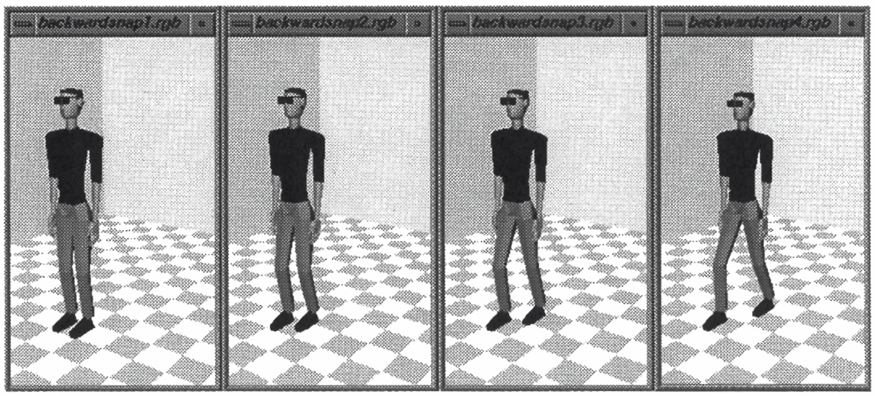

Figure 11: The Four Snapshots during a Backward Step

8 Acknowledgments

This research is partially supported by ARO Grant DAAL03-89-C-0031 including participation by the U.S. Army Human Engineering Laboratory, Natick Laboratory, and NASA Ames Research Center; U.S. Air Force DEPTH contract through Hughes Missile Systems F33615-91-C-0001; MOCO Inc.; and NSF CISE Grant CDA88-22719. Partial support for this work was provided by the National Science Foundation's Instrumentation and Laboratory Improvement Program through Grant number USE-9152503.

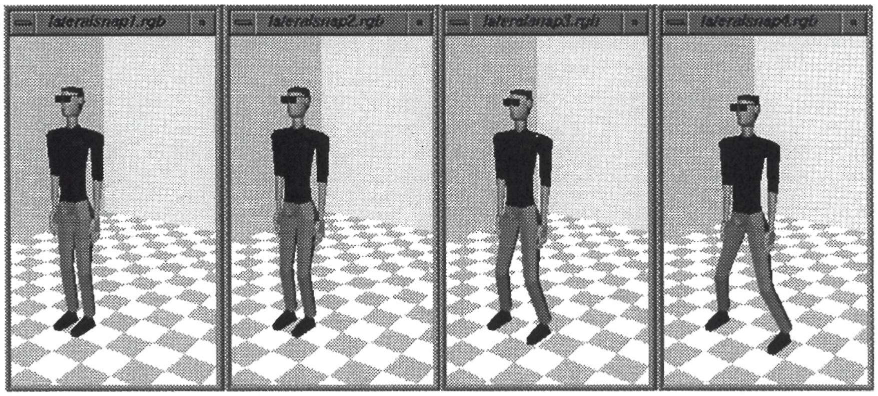

Figure 12: The Four Snapshots during a Lateral Step

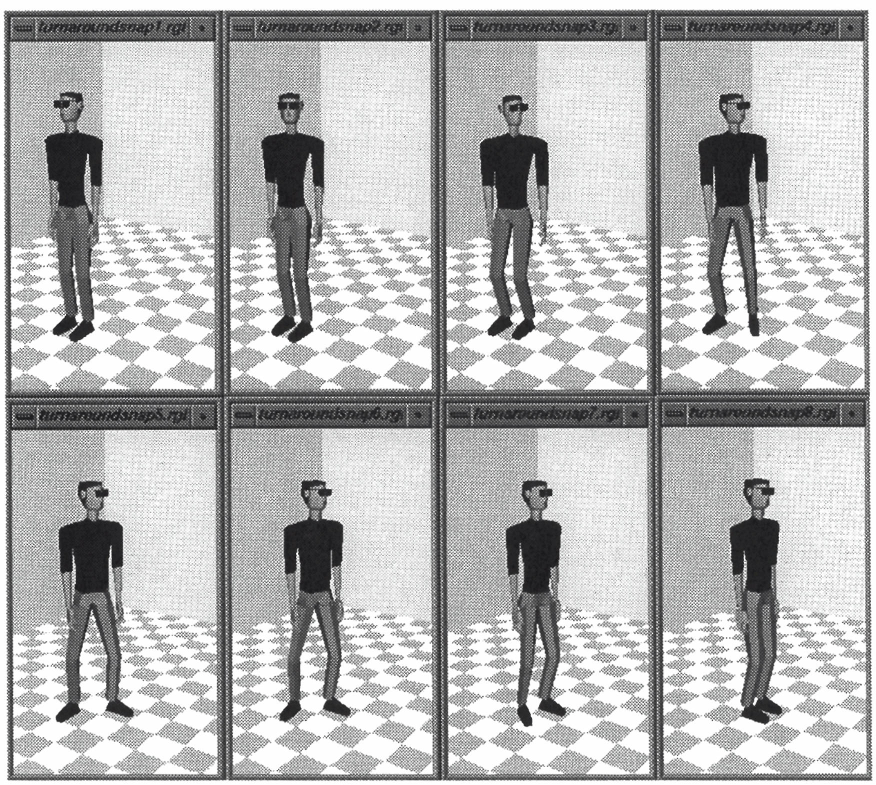

Figure 13: The Eight Snapshots during a Turnaround

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