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Comments

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Intermittent Non-Rhythmic Human Stepping and Locomotion

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GRAPHICS LAB 55

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Abstract

There are many occasions where non-rhythmic stepping (NRS) is more desirable than normal walking. This can be observed in performing tasks in a narrow 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. 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 in INITIALIZE_NRS before each NRS begins. ADVANCE_NRS 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, algorithm, trajectory.
1 Introduction

Human locomotion occupies a large part of human activities. The basis of it is linear path locomotion (LPL). Bruderlin and Calvert built a keyframeless locomotion system for straight walking paths [3, 2]. 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 [1]. 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. Ko and Badler [8] 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 is mostly a curve. Girard discussed the turning problem in [5]. He interprets the stepping (liftoff) as a way to exert an impulse on the human body in running. Each impulse contributes an acceleration to the whole body movement. He computed the impulse that is required to drive the center of the body along a given curve. By the impulse (which includes rotational torque as well as upward force) at the liftoff, the body gets a rotational as well as translation movement. Ko and Badler developed a CPL algorithm that uses an underlying LPL as a subroutine [9]. 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. We will call this non-rhythmic stepping (NRS).

NRS turns out to be very useful in the three dimensional animation of human behaviors, as the transition between tasks. 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 NRS would be more
appropriate than normal walking for the motion between the grasping and final putting down. However, this problem has not been tackled much yet. We propose a solution based on 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 during a long walk, NRS can be useful. For instance, if the agent should abruptly reverse the direction during walking, it is more effective to turnaround and walk away than to walk along a smoothly curved path. If there is a tight turn during a walk, the step deviates from the normal walking pattern too much. In this case, the non-rhythmic forward stepping above produces better result.

Some terminology needs to be defined here. 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. If a leg is between the other leg’s heelstrike (beginning) and its own heelstrike (ending), it is called the swing leg. For example, in Figure 1, left leg is the stance leg during the interval 1, and right leg is the stance leg during the 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 [2, 3] when the toes begin to rotate around the tip of the toe, and $TOM$ be the Toe Off Moment.

Our LPL and CPL systems are introduced in the following two sections. The overview of generating NRS will be shown in Section 4. The input parameters that specifies the motion of NRS are listed in Section 5. The details of $NRS^-$ and turnaround will be explained in Section 6 and Section 7, respectively.

2 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, 12, 11]), measuring ([17, 16]), simulating ([15]) human walking, or even making a robot that takes steps ([7, 14]). Among those, data collected from measurements of a subject’s walking is used in our LPL [8]. The most popular measuring technique nowadays is so called rotoscoping. Because the measurements are performed on a finite number of subjects and steps, without a method to generate the steps of other anthropometry and other step lengths, its value is rather limited in the computer animation field.

We created a generalization which can produce the steps of an arbitrary anthropometry and an arbitrary step length from a measured data set of one particular subject and one particular step. The original style of the walking motion is mostly (completely in mathematical sense) preserved during the generalization. The preservation of motion style is defined in the following paragraph.

Suppose we have a measured data set $W(S_1, s_{l1})$ of the subject $S_1$ at the step length $s_{l1}$. And suppose we have produced the data $W(S_2, s_{l2})$ through the generalization of $W(S_1, s_{l1})$. When another step data $W(S_3, s_{l3})$ should be generated, most people may use the original measured one $W(S_1, s_{l1})$ rather than the generalized one $W(S_2, s_{l2})$ as the input of the generalization process, because some characteristics of the original motion might have been lost in $W(S_2, s_{l2})$. However, if both of $W(S_1, s_{l1})$ and $W(S_2, s_{l2})$ produce the same result in generating $W(S_3, s_{l3})$, then we may consider the original characteristics of $W(S_1, s_{l1})$ are preserved in $W(S_2, s_{l2})$. Furthermore, if the above is true for any $(S_2, s_{l2})$ and $(S_3, s_{l3})$ (transitive), then $\hat{W}(S_n, s_{l_n})$ after the series of generalizations $(W(S_1, s_{l1}), W(S_2, s_{l2}), \ldots, \hat{W}(S_n, s_{l_n}))$ will be the same with $\hat{W}(S_n, s_{l_n})$ after the direct generalization $(W(S_1, s_{l1}), \hat{W}(S_n, s_{l_n}))$. The transitivity can be regarded as a measure of
characteristic preservation in the generalization of experimental data.

Our generalization algorithm has been proved [8] to preserve the characteristics of the original walking data. Our LPL can be extended incrementally: because it basically imitates the original motion, we can simulate different locomotion styles by acquiring multiple sets of measurements. Thus, in one scene, several people can walk in their own walking patterns.

3 Curved Path Locomotion

We attempted a further generalization from LPL to curved path locomotion (CPL) [9]. In building a CPL system, we tried to utilize pre-existing LPL systems. That is, an LPL system is used as a subsystem to our 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. \textit{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.

There are two primitives for generating each walking step: \texttt{INITIALIZE\_STEP(walker, next\_foot\_print, left\_or\_right, step\_duration)} and \texttt{ADVANCE\_STEP(walker,normalized\_time)}. Each step is initialized by \texttt{INITIALIZE\_STEP}, which precomputes the trajectories of the hips and ankles that will be referenced in \texttt{ADVANCE\_STEP} later. In \texttt{INITIALIZE\_STEP}, \texttt{walker} specifies the walker to be initialized for the step. This way there can be multiple walkers in the same scene. \texttt{next\_foot\_print} is the location of the foot print to be achieved by the current step. \texttt{left\_or\_right} designates which foot (and leg) is used in the current step. The duration of the step is given by \texttt{step\_duration}.

\texttt{ADVANCE\_STEP} generates the walking poses of \texttt{walker} at the given \texttt{normalized\_time}. \texttt{normalized\_time} is the logical time: \texttt{ADVANCE\_STEP(walker,0.0)} gives the pose at the beginning of the current step and \texttt{ADVANCE\_STEP(walker,1.0)} gives the one at the end of the current step. By increasing \texttt{normalized\_time} from zero to one, the walking motion of a whole step can be generated. The step size $\Delta t$ of \texttt{normalized\_time} can be adjusted. It is a very effective
way to adapt to the various machine speeds for realtime interactive walking display. The concept of normalized time proved to be intuitive and easy to use for the animators.

Our CPL algorithm is a constant time algorithm (excluding LPL computation) per step, and it can be used as a filter on top of an LPL system. Experiments prove that this method is very robust and the walking motion is quite realistic. Also this method enables people to study the straight line walking independently from the curved path walking. This method is an effective and practical way of producing curved path human locomotion.

4 Overview of NRS Generation

As in CPL, we have 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. specs and specs' are the input parameters that specifies the details of an NRS- and a turnaround, respectively.

The center site is defined as the mid-point of the two hip joints. In the movement of the lower body, the trajectories of the center site and the ankles determine the basic outline of stepping motion. These trajectories are precomputed within INITIALIZE_NRS (INITIALIZE_NRS- and INITIALIZE_TURNAROUND).

ADVANCE_NRS (ADVANCE_NRS- and ADVANCE_TURNAROUND) is called at each normalized time step t: first, 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 next three sections are about generating NRS motion. The topmost level specification of an NRS is dealt with in Section 5. Sections 6 and 7 describes the details of NRS- and turnaround, respectively.
Figure 2: The Four Regions that Determine the Type of an NRS

5 Input Specification of NRS

We use the following tuple, specs, to describe an NRS.

\[
\text{specs} = (\text{footpos}, \text{footdir}, \text{left_or_right}, \text{swhf}, \text{eye_gaze_dir}, \tilde{\theta}_\text{foot})
\] (1)

\text{footpos} and \text{footdir} are the goal position and direction of the stepping foot. \text{left_or_right} is left when the stepping leg is the left one and right otherwise. These three parameters \text{specs}_1 = (\text{footpos}, \text{footdir}, \text{left_or_right}) in \text{specs} are fundamental, and without them stepping cannot be shaped. However, there are various ways to achieve the step specified by \text{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 more parameters \text{specs}_2 = (\text{swhf}, \text{eye_gaze_dir}, \tilde{\theta}_\text{foot}). These detailed parameters can be extended later to include other details. The swing height factor \text{swhf} tells how high the swing foot trajectory should be compared with 5\text{cm}. If \text{swhf} is 1, then the maximum height component of the stepping is 5\text{cm}, 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. \text{eye_gaze_dir} is the direction of eye contact at the end of the NRS. \tilde{\theta}_\text{foot} is used to specify the foot angles during the NRS. It will be explained in Subsection 6.1

NRS has three types: forward, backward, and lateral. It is automatically determined from the current stance foot position and direction, and \text{footpos}, as shown in Figure 2. The four regions, forward, lateral, backward, and illegal, are defined by the four lines crossing at the stance heel position, and making the angles \nu (constant) in the favored side, and 0.5\nu in the unfavored side, with the direction of the stance foot. Depending on where \text{footpos} falls, we determine the stepping
The Foot Angle Pattern during a Walking Step

Figure 3: The Foot Angle Pattern during a Walking Step

type. At the boundaries, 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, \( \nu \) is set to 60 deg.

For the turnaround, we need a different specification

\[
\text{specs}' = (\text{angle}, \text{left_or_right}, \text{type})
\]

where \( \text{angle} \) is the amount of turn in degrees, and \( \text{left_or_right} \) is the direction of the turnaround. \( \text{type} \) will be explained in Section 7. Turnaround takes two steps: the first one makes the body twisted by the \( \text{angle} \), and the next one recovers the normal stance. If \( \text{left_or_right} \) 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 \( \text{left_or_right} \) is right is similar.

6 NRS–

In this section we show how an NRS– described by \( \text{specs} \) is generated. Subsections 1 through 3 show how the three basic trajectories are formed in \text{INITIALIZE.NRS}–. Subsection 4 shows how it can draw the pose at normalized time \( t \) in \text{ADVANCE.NRS}–. Within this section, we may use NRS for NRS–, for notational simplicity.
6.1 Foot Angles

Let's first look at the pattern of the foot angles in human walking. According to Inman's study ([6]), they follow the pattern shown in Figure 3. The first piece $C^{ST}$ of the curve in the figure is for the stance foot, and the second one $C^{SW}$ is for the swing foot.

Similar curve pieces, $C^{ST}_{WALKING}$ and $C^{SW}_{WALKING}$, of the underlying walking step of the current NRS are provided by the CPL algorithm in Section 3, regarding the current NRS as a walking step. $C_{WALKING}$ will be used to denote $C^{ST}_{WALKING}$ and $C^{SW}_{WALKING}$ together. Similar notational conventions $C^{ST}_{NRS}$, $C^{SW}_{NRS}$ and $C_{NRS}$ will be used for the NRS.

The foot angle in an NRS may be different from the one in normal walking. For example, in forward stepping, the foot may stay more parallel to the ground than in walking. Such variations in foot angle are controlled by the vector $\vec{\theta}_{foot} = (\hat{\theta}^{ST}_{HSM+}, \hat{\theta}^{SW}_{TOM}, \hat{\theta}^{SW}_{HSM+})$, which was the last element of the input parameters specs. $\hat{\theta}^{ST}_{HSM+}$ is the stance foot angle (foot sole angle) at $HSM^+$, $\hat{\theta}^{SW}_{TOM}$ is the swing foot angle at $TOM$, and $\hat{\theta}^{SW}_{HSM+}$ is the swing foot angle at $HSM^+$ (Figure 4).

Let $\theta^{ST}_{HSM-}$, $\theta^{ST}_{HSM+}$, $\theta^{SW}_{HSM-}$, $\theta^{SW}_{TOM}$, and $\theta^{SW}_{HSM+}$ be the stance foot angles at $HSM^-$, $HSM^+$, the swing foot angles at $HSM^-$, $TOM$, and $HSM^+$, respectively, of the underlying walking step. Note that the actual stance foot angle $\hat{\theta}^{ST}_{HSM-}$ and the swing foot angle $\hat{\theta}^{SW}_{HSM-}$ of the forward stepping at $HSM^-$ in $C_{NRS}$ are given through the initial pose just before the stepping, and may be different from $\theta^{ST}_{HSM-}$ and $\theta^{SW}_{HSM-}$ in $C_{WALKING}$, respectively. Likewise, $\hat{\theta}^{ST}_{HSM+}$, $\hat{\theta}^{SW}_{TOM}$, $\hat{\theta}^{SW}_{HSM+}$ in $C_{NRS}$ can be different from $\theta^{ST}_{HSM+}$, $\theta^{SW}_{TOM}$, and $\theta^{SW}_{HSM+}$ in $C_{WALKING}$, respectively.
Let $F_{S_{NRS}}$ and $F_{S_{NRS}}$ be the sets of points that $C_{S_{NRS}}^{ST}$ and $C_{S_{NRS}}^{SW}$ will go through, respectively:

$$F_{S_{NRS}} = \{(HSM^-, \ddot{\theta}_{HSM}^-),(HSM^+, \ddot{\theta}_{HSM}^+)\}$$  \hspace{1cm} (3)  
$$F_{S_{NRS}}^SW = \{(HSM^-, \ddot{\theta}_{HSM}^-),(TOM, \ddot{\theta}_{TOM}^+),(HSM^+, \ddot{\theta}_{HSM}^+)\}$$  \hspace{1cm} (4)

We want to modify $C_{WALKING}$ so that it may satisfy the end point constraints $\ddot{\theta}_{foot}$. That is, we modify the two curves $C_{WALKING}^{ST}$ and $C_{WALKING}^{SW}$ so that they pass through the sets of points $F_{S_{NRS}}^{ST}$ and $F_{S_{NRS}}^{SW}$, respectively. We can identify monotonic segments in the two pieces of the curve. Let $C_{[HSM^-, FGM]}^{(ST, WALKING)}$, $C_{[FGM, HSM^+]}^{(ST, WALKING)}$ be the two monotonic segments of $C_{WALKING}^{ST}$. The first one is from $HSM^-$ to $FGM$, and the second one covers the other part of the interval. Let $C_{[HSM^-, TOM]}^{(SW, WALKING)}$, $C_{[TOM, HSM^+]}^{(SW, WALKING)}$ be the two monotonic segments of $C_{WALKING}^{SW}$. We define the foot angle trajectory of the NRS as follows:

$$C_{[HSM^-, FGM]}^{(ST, NRS)}(t) = C_{[HSM^-, FGM]}^{(ST, WALKING)}(t) + (1 - t)(\ddot{\theta}_{HSM}^- - \ddot{\theta}_{HSM}^+)$$  \hspace{1cm} (5)  
$$C_{[FGM, HSM^+]}^{(ST, NRS)}(t) = C_{[FGM, HSM^+]}^{(ST, WALKING)}(t) + t(\ddot{\theta}_{HSM}^+ - \ddot{\theta}_{HSM}^-)$$  \hspace{1cm} (6)  
$$C_{[HSM^-, TOM]}^{(SW, NRS)}(t) = C_{[HSM^-, TOM]}^{(SW, WALKING)}(t) + (1 - t)(\ddot{\theta}_{HSM}^- - \ddot{\theta}_{HSM}^+) + t(\ddot{\theta}_{TOM}^- - \ddot{\theta}_{TOM}^+)$$  \hspace{1cm} (7)  
$$C_{[TOM, HSM^+]}^{(SW, NRS)}(t) = C_{[TOM, HSM^+]}^{(SW, WALKING)}(t) + (1 - t)(\ddot{\theta}_{TOM}^- - \ddot{\theta}_{TOM}^+) + t(\ddot{\theta}_{HSM}^+ - \ddot{\theta}_{HSM}^-)$$  \hspace{1cm} (8)

where $t$ in each formula is normalized within the corresponding interval. For example, in defining $C_{[HSM^-, FGM]}^{(ST, NRS)}$, $t$ is 0 at $HSM^-$, and 1 at $FGM$. Finally, $C_{NRS}^{ST}$ and $C_{NRS}^{SW}$ are defined by concatenating $C_{[HSM^-, FGM]}^{(ST, NRS)}$ and $C_{[FGM, HSM^+]}^{(ST, NRS)}$, $C_{[HSM^-, TOM]}^{(SW, NRS)}$ and $C_{[TOM, HSM^+]}^{(SW, NRS)}$, respectively. The basic idea in the above formulation is to follow the outline of the original curves while making the constraints satisfied at the ends of each monotonic segment.

6.2 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:

$$f(t) = \frac{\text{swfh}}{e^\frac{1}{2} + e^{-\frac{1}{2} - e^{t - \frac{1}{2}} - e^{-t + \frac{1}{2}}}$$  \hspace{1cm} (9)

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 [4] 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 the point which is displaced from the stance ankle by $2\lambda$ in the perpendicular direction of $D_1D_3$ as shown in Figure 5. Here $2\lambda$ 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.

6.3 Hip Trajectory

The planar hip trajectory is a straightforward approximation by a line segment. As mentioned earlier, because of no imposed pattern in NRS, this approximation works well. According to the stepping type, however, the height component of the hip trajectory varies. In lateral stepping, the hip 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 hip height trajectory $\{(t_i, h_i) \mid i = 1, \ldots, n\}$ of the underlying walking step of the NRS. Let $h_{WALKING}^{HSM^-} = h_1$ and $h_{WALKING}^{HSM^+} = h_n$ (Figure 6). Given the foot angles in Subsection 6.1, we can compute the location of the ankles at $HSM^-$ and $HSM^+$ of the NRS. Assuming that the knee flexion of the NRS and the underlying walking step are the same at $HSM^-$ and $HSM^+$, respectively, we can compute the hip heights $h_{NRS}^{HSM^-}$ and $h_{NRS}^{HSM^+}$ of the NRS at those moments.
Finally, the hip height trajectory \( \{ (t_i, h'_i) | i = 1, \ldots, n \} \) of the NRS is obtained by the interpolation

\[
h'_i = h_i + (1 - t_i)(h^N_{NRS} - h^N_{WALKING}) + t_i(h^F_{NRS} - h^F_{WALKING})
\]

As the accompanying animation demonstrates, we can get an acceptable backward walking animation by just playing the forward walking animation in reverse. Based on this, we use a similar method as in the forward step to get the 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. And the interpolation is given by

\[
h'_i = h_{n-i+1} + (1 - t_i)(h^F_{NRS} - h^F_{WALKING}) + t_i(h^N_{NRS} - h^N_{WALKING})
\]

### 6.4 Lower Level Details

For each normalized time \( t \), ADVANCE_\text{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 \( 0.5\alpha \), where \( \alpha \) is the angle between the lateral direction and the line between the stance foot and 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 $\text{eye.gaze.dir}$. Now, the angle of the eye gaze direction relative to the pelvis (facing) direction can be computed. In our work, $\frac{2}{3}$ 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.

7 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. Therefore 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 $2\lambda$ back and left of the right foot, facing the goal direction. In the next step the right foot is located $2\lambda$ front and right of the resulting left foot, facing the goal direction. Putting
the second stepping foot $2\lambda$ 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 task like grasping. This is the *stationary* type. The case of the right turn is similarly determined. Figure 8 shows two examples: 90 degree left and right turnarounds (dynamic type). $F_L^i$, $F_R^i$ are the initial left and right feet, and $F_L^f$, $F_R^f$ are the ones after the turnaround. Note that the original positions $F_L^i$ and $F_R^i$ 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). Suppose $\delta$ is the duration of the first step of a turnaround. The torso and head begins to rotate to the goal direction $0.5\delta$ before the first step begins. During the first $\delta$, the gaze direction changes from the initial direction to the goal direction. Therefore the anticipation and the first step overlap during $0.5\delta$, and the total time taken for a turnaround is $2.5\delta$. Once the eye gaze direction is determined by an interpolation at each time step, the torso and neck are twisted as in Subsection 6.4.

**Figure 8:** 90 Degrees Left and Right Turnarounds

**Figure 9:** The Timing of the Anticipation in a Turnaround
8 Implementation and Conclusion

The four types of NRS are implemented in Jack™ [13]. Snap shots during a forward, backward, lateral steps, and turnaround are shown in Figures 10, 11, 12, and 13, respectively. NRS has proved to be very useful in animating the general human behaviors where small steps are needed occasionally in a narrow space. It introduces a lot of adjustability. The resulting motion turns out to be reasonably realistic.

9 Acknowledgments

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Figure 11: The Four Snapshots during a Backward Step

Figure 12: The Four Snapshots during a Lateral Step
Figure 13: The Eight Snapshots during a Turnaround
References


