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Reliable Forward Walking Parameters from Head-Track Data Alone

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ABSTRACT

Head motion during real walking is complex: The basic translational path is obscured by head bobbing. Many VE applications would be improved if a bobbing-free path were available. This paper introduces a model that describes head position while walking in terms of a bobbing free path and the head bobs. We introduce two methods to approximate the model from head-track data.

1 INTRODUCTION

To accurately present view-dependent virtual environments (VEs), VE systems must track the user's head position. Due to cost and setup time, many VE systems track only the head. Walking-induced head bobs mask useful parameters like walk speed and walk direction (Figure 1). Other useful parameters such as step frequency and step timings are not directly available via head-tracking alone. In this paper, we present a model that results in estimates for these parameters using only head-track position data.

The motion of the head while walking is governed by the biomechanics of bipedal locomotion [1]. After basic translation, the most prominent characteristic of the head's walking motion is *head bobbing* with its three signed, orthogonal components: right-left (hereafter "rightward"), fore-aft (hereafter "forward"), and up-down (hereafter "upward"). Although bobbing complicates generating a good estimate of the user's instantaneous speed and direction (Figure 1), it can aid in estimating step frequency and step timings.

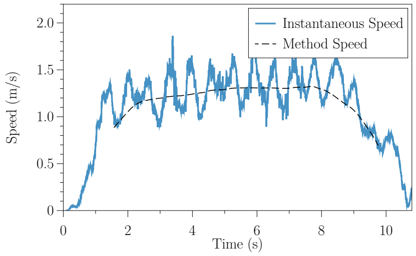
These VE applications can benefit from reliable walking parameter estimates:

Animating Self Avatars: Usoh et al. [7] found a significant correlation between presence and the subjects' degree of association with their avatars. Lacking full-body tracking in most systems, we believe that our methods' outputs could be used to generate plausible self-avatar walking animations from head-track data alone.

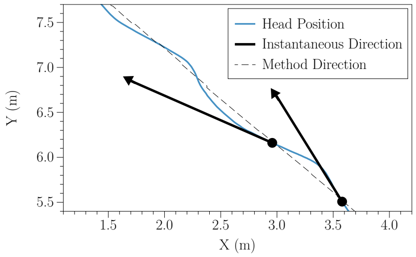
Redirected Walking: Redirected Walking enables users to explore large virtual worlds by disassociating the real-world path from the virtual-world path and imperceptibly redirecting users toward open space [4]. Redirection needs accurate position, walk direction, and speed – parameters provided by our methods.

Walking-In-Place (WIP): WIP systems create virtual-world movement based on a user's in-place steps [6]. Our GUD WIP system can create virtual walk speeds tuned to any user if a per-user walk-speed-to-step-frequency function is available [8]. Our methods can create such functions automatically as a user walks.

Post hoc analysis: Our methods could improve post-hoc analysis of head-tracked locomotion logs generated in comparative user studies (e.g. [9, 5]). For instance, to remove head bobs from walking paths, Whitton heavily smoothed the data – removing both head bobbing and higher frequency components of the bobbing-free path [9]. Our methods remove head bobs with minimal smoothing.



(a) Walk Speed



(b) Walk Direction

Figure 1: The instantaneous (a) horizontal walk speed (solid, lighter line) and (b) over-head-view of walk direction (thicker sold lines) compared to our method's output (dashed lines).

2 THE FORWARD WALKING MODEL

Our Forward Walking Model is based on the biomechanics of human walking [1]. Mathematically, forward-walking dynamic head positions ($\mathbf{h}(t)$) are the combination of the three bobbing components ($\mathbf{B_r}(t)$, $\mathbf{B_f}(t)$, $\mathbf{B_u}(t)$, for rightward, forward, and upward bobbing, respectively) and the remaining translation ($\mathbf{T}(t)$):

$$\mathbf{h}(t) = \mathbf{B_r}(t) + \mathbf{B_f}(t) + \mathbf{B_u}(t) + \mathbf{T}(t) \tag{1}$$

Each of the bobbing components can be estimated by a sinusoid:

$$\mathbf{B_v}(t) = \mathbf{v}(t) \cdot a_{\mathbf{v}}(t) \cdot \sin\left(2\pi f_{\mathbf{v}}(t) \cdot (t - t_0) + \phi_{\mathbf{v}}(t)\right) \tag{2}$$

where $\mathbf{v}$ is the direction vector, $a_{\mathbf{v}}$ is amplitude, $f_{\mathbf{v}}$ is frequency, $\phi_{\mathbf{v}}$ is phase, and t_0 is a centering term. Each varies with time.

The rightward ($\mathbf{r}$), forward ($\mathbf{f}$), and upward ($\mathbf{u}$) direction vectors define a body-centric walking space related to the world-centric forward direction in the horizontal plane by an angle (θ):

$$\left[\begin{array}{c|c|c} \mathbf{r}(t) & \mathbf{f}(t) & \mathbf{u}(t) \end{array}\right] = \left[\begin{array}{c|c|c} \cos(\theta(t)) & -\sin(\theta(t)) & 0 \\ \sin(\theta(t)) & \cos(\theta(t)) & 0 \\ 0 & 0 & 1 \end{array}\right] \tag{3}$$

Equation 2 is constrained by biomechanics principles. The forward and upward bobs' frequency match the step frequency (f_s); the rightward bob moves at one-half the step frequency ($f_s/2$).

If bobbing is removed from Equation 1, only the forward translation ($\mathbf{T}$) remains. Forward translation is estimated as a bobbing-free head position ($\mathbf{c}$), and a forward speed (s):

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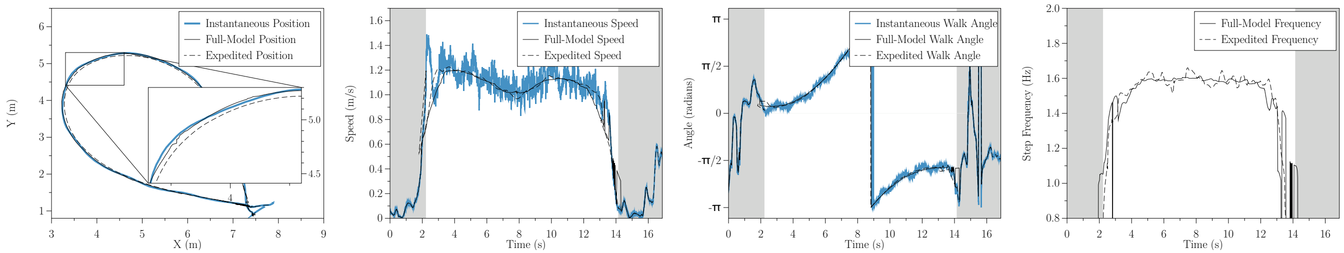

(a) Overhead Position (b) Walk Speed (c) Walk Direction (d) Step Frequency

Figure 2: Our two approximation methods' results. User walked a loop. Thicker, lighter line: head-track data. Thinner, darker line: Full-Model-Fit Method. Dashed-line: Expedited Method. (a) Overhead view with magnification inset. (b) Walk speed. (c) Walk Direction. (d) Step Frequency. Note that although the Expedited bobbing-free position is somewhat less accurate than the Full-Model's, the Expedited Method's position is provided with approximately half the latency.

$$\mathbf{T}(t) = \mathbf{c}(t) + \mathbf{f}(t)\cdot(s(t)\cdot(t-t_0)) \tag{4}$$

$$\mathbf{c}(t) = \begin{bmatrix} c_{\mathbf{x}}(t) & c_{\mathbf{y}}(t) & c_{\mathbf{z}}(t) \end{bmatrix}^{\mathrm{T}} \tag{5}$$

Finally, to better fit curved walking paths, we enhance $\theta(t)$ in Equation 3 with an angular velocity term ($\omega(t)$):

$$\theta(t) + \omega(t)\cdot dt \tag{6}$$

The full model of walking-induced head motion is found by expanding Equation 1 with Equations 2–6:

$$\begin{aligned} \mathbf{h}(t) = &\begin{bmatrix} \cos(\theta(t)+\omega(t)\cdot dt) \\ \sin(\theta(t)+\omega(t)\cdot dt) \\ 0 \end{bmatrix} (a_{\mathbf{r}}(t)\cdot \sin(\pi f_s(t)\cdot(t-t_0)+\phi_{\mathbf{r}}(t))) + \\ &\begin{bmatrix} -\sin(\theta(t)+\omega(t)\cdot dt) \\ \cos(\theta(t)+\omega(t)\cdot dt) \\ 0 \end{bmatrix} (a_{\mathbf{f}}(t)\cdot \sin(2\pi f_s(t)\cdot(t-t_0)+\phi_{\mathbf{f}}(t))) + \\ &\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} (a_{\mathbf{u}}(t)\cdot \sin(2\pi f_s(t)\cdot(t-t_0)+\phi_{\mathbf{u}}(t))) + \\ &\begin{bmatrix} c_{\mathbf{x}}(t) \\ c_{\mathbf{y}}(t) \\ c_{\mathbf{z}}(t) \end{bmatrix} + \begin{bmatrix} -\sin(\theta(t)+\omega(t)\cdot dt) \\ \cos(\theta(t)+\omega(t)\cdot dt) \\ 0 \end{bmatrix} (s(t)\cdot(t-t_0)) \end{aligned} \tag{7}$$

3 APPROXIMATION METHODS

We created two methods for approximating Equation 7: the Full-Model-Fitting, and Expedited Methods. Both estimate some parameters by fitting via the Levenberg-Marquardt Algorithm – a numerical method for function minimization [2, 3]. Briefly, we fit a fixed-width time window of head-track data to Equation 7. In the Full-Model-Fitting Method, all parameters are fit at once. In the Expedited Method, only the vertical parameters are fit, with some remaining parameters approximated using the vertical fit's results.

Both methods run in real time. The Full-Model-Fitting Method provides estimates for all model parameters, but requires a larger window size (1.5 s) – increasing the estimates' latency. The Expedited Method uses a smaller window size (~0.75 s), but does not estimate all parameters. Figure 2 compares these methods' results.

4 VALIDATION AGAINST REAL-WALKING DATA

We validated the automatic results from our methods against those manually calculated against real-walking head-track data from a previous study [8]. Our approximation methods' results provided bobbing-free walk speed, bobbing-free walk direction, and step frequency estimates within 5% accuracy of the manually analyzed data in 85% of our trials, and within 10% accuracy in 96% of our trials.

5 CONCLUSION

We suggest that our methods could improve four VE applications: animated self avatars, Redirected Walking, WIP systems, and post-hoc analyses. We have already begun further research to incorporate this work into these systems and analyze improvements. In this work, we demonstrated that important walking parameters can be reliably extracted from head-track data alone.

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