An adaptive model of sensory integration in a dynamic environment applied to human stance control

Herman van der Kooij¹, Ron Jacobs¹,², Bart Koopman¹, Frans van der Helm¹,³

¹ Institute of Biomedical Technology, University of Twente, PO Box 217, 7500 AE Enschede, The Netherlands
² Intelligent Inference Systems Corporation, 107 West 333 Maude Avenue, Sunnyvale, CA 94086, USA
³ Man-Machine Systems and Control Group, Delft University of Technology, Mekelweg 2, 2628 CD Delft, The Netherlands

Received: 12 November 1999 / Accepted in revised form: 30 June 2000

Abstract. An adaptive estimator model of human spatial orientation is presented. The adaptive model dynamically weights sensory error signals. More specific, the model weights the difference between expected and actual sensory signals as a function of environmental conditions. The model does not require any changes in model parameters. Differences with existing models of spatial orientation are that: (1) environmental conditions are not specified but estimated, (2) the sensor noise characteristics are the only parameters supplied by the model designer, (3) history-dependent effects and mental resources can be modelled, and (4) vestibular thresholds are not included in the model; instead vestibular-related threshold effects are predicted by the model. The model was applied to human stance control and evaluated with results of a visually induced sway experiment. From these experiments it is known that the amplitude of visually induced sway reaches a saturation level as the stimulus level increases. This saturation level is higher when the support base is sway referenced. For subjects experiencing vestibular loss, these saturation effects do not occur. Unknown sensory noise characteristics were found by matching model predictions with these experimental results. Using only five model parameters, far more than five data points were successfully predicted. Model predictions showed that both the saturation levels are vestibular related since removal of the vestibular organs in the model removed the saturation effects, as was also shown in the experiments. It seems that the nature of these vestibular-related threshold effects is not physical, since in the model no threshold is included. The model results suggest that vestibular-related thresholds are the result of the processing of noisy sensory and motor output signals. Model analysis suggests that, especially for slow and small movements, the environment postural orientation can not be estimated optimally, which causes sensory illusions. The model also confirms the experimental finding that postural orientation is history dependent and can be shaped by instruction or mental knowledge. In addition the model predicts that: (1) vestibular-loss patients cannot handle sensory conflicting situations and will fall down, (2) during sinusoidal support-base translations vestibular function is needed to prevent falling, (3) loss of somatosensory information from the feet results in larger postural sway for sinusoidal support-base translations, and (4) loss of vestibular function results in falling for large support-base rotations with the eyes closed. These predictions are in agreement with experimental results.

1 Introduction

To control posture, postural orientation must be known. Humans utilise multiple sources of sensory information to orient themselves in space. When the visual scene or support base is fixed, visual or proprioceptive information is sufficient to define postural orientation with respect to the gravitational axis and both can stabilise posture (e.g. Peterka and Benolken 1995; Ishida et al. 1997). However, support-base rotation or visual scene movement destabilise posture (e.g. Berthoz et al. 1979; Bolha et al. 1999).

Proprioceptive and visual clues alone are insufficient to distinguish ego-motion, visual scene and support-base motion from each other. In that case the vestibular system appears to be crucial in distinguishing ego-motion from environmental motion (see also Mergner et al. 1991, 1992, 1995). This is demonstrated by experiments in which for large movements of the visual scene (Peterka and Benolken 1995) or large platform rotations (Maurer and Mergner 1999), vestibular-loss patients – in contrast with normals – were not able to maintain balance. By the nature of the vestibular system, it is impossible to get an ideal estimate of orientation of the head in space, especially for low-frequency movements (Cohen et al. 1973; Mergner and Glasauer 1999). In most models of the
vestibular system this non-ideal low-frequency behaviour is included as a physical threshold (e.g. Borah et al. 1988; Nashner et al. 1989; Hosman 1996). However, these thresholds are based on perceptual thresholds for egomotion obtained from psychophysical studies (e.g. Clark and Stewart 1969). There is evidence that vestibular-related thresholds are of central origin and depend on other sensory clues (Mergner et al. 1995).

Among others (Borah et al. 1988; Gerdes and Happes 1994; Wolpert et al. 1995), we have described the complex process of human spatial orientation with the use of optimal estimation theory (Van der Kooij et al. 1999a). According to this view the control model has a kind of internal representation (IR) which includes ‘knowledge’ of the body and sensor dynamics, and the external environment. Using this representation the control model makes an estimate of spatial orientation using both the motor and sensory output signals. These sensory and motor signals are integrated so that a minimum variance estimate of postural orientation is obtained. Spatial orientation under various illusory sensations (Borah et al. 1988) and specific multivariate changes of postural sway due to altered visual or platform perturbation conditions (Van der Kooij et al. 1999b) can be predicted using optimal estimation theory. Optimal estimation theory, however, does not fully explain how humans integrate multisensory information. By using optimal estimation theory some ‘knowledge’ is required of the precision of the different sensory systems and of the external environment acting upon the body and the sensory system. This ‘knowledge’ is usually specified by power spectral density matrices of the sensor noise and of the disturbances acting on the body. These matrices are defined by the designer of the optimal estimator (Kalman filter) and are usually used as design variables. It is easy and tempting to use these power spectral matrices to match model predictions with experimental results. In models using a Kalman filter to model spatial orientation, the system and sensor noise statistics are used as ‘tuning parameters’ to mimic model with experimental results (Borah et al. 1988; Gerdes and Happes 1994; Wolpert et al. 1995). The statistical properties of external forces, support-base translations and rotation, and visual scene motion have to be specified in the human stance control model in order to obtain a minimum variance estimate of spatial orientation. The intriguing question of how humans solve the problem of distinguishing ego-motion from motion of the environment can not be understood within the concept of a non-adaptive observer like the (extended) Kalman filter; when using a Kalman filter the statistical properties of environmental motion are specified by the model designer.

Therefore, in this paper an adaptive estimator model of human spatial orientation is presented where, besides spatial orientation, ‘knowledge’ of the external environment is estimated from the sensory output signals instead of being specified by the designer. Only the sensor noise characteristics have to be specified by the model designer. We believe that the modified model is biologically more realistic. The model is used to investigate:

1. Whether it is possible to estimate postural orientation based on sensory information only and use this estimate to stabilise posture, without specifying environmental conditions as is done in existing models of spatial orientation.
2. Whether sensor noise properties can be found by matching model predictions with experimental results.
3. Whether the model produces vestibular-related thresholds without including physical thresholds.
4. Whether vestibular-related thresholds can be understood by the noisy properties of the sensory signals.
5. How sensory loss affects postural control and orientation under different environmental conditions.
6. Whether experience and cognitive resources can be modelled within this model, and how they influence postural orientation and control.

2 Methods

Optimal estimator models of spatial orientation are usually realised by including a Kalman filter (KF). The working of the KF is a combination of two processes. The first process uses the current estimate of spatial orientation and motor outflow to predict the next estimate of spatial orientation, by simulating the dynamics using an Internal Model (IM) of the body and environment. The second process uses an IM of the sensory dynamics to predict the sensory output corresponding to this predicted next estimate. The sensory error – the difference between actual and predicted sensory output – is weighted by the Kalman gain to drive the estimate of spatial orientation, resulting from the first process, to its true value. The elements of the Kalman gain are determined by the uncertainty in the predicted next estimate (caused for example by an imperfect IM or uncertainties of the environmental conditions) and the uncertainty in a sensory output signal. These uncertainties are specified by the designer of the KF as power spectral density matrices of the sensor noise and of the external environmental variables acting on the body. We modified our human stance control model (Van der Kooij et al. 1999a) by replacing the KF with an adaptive KF. In the original model the statistical properties of mechanical disturbances, platform rotation and accelerations and visual scene motion, had to be specified by the model designer. In the modified model these statistical properties of the environment acting on the body are estimated by the adaptive KF simultaneously with the estimate of spatial orientation based on sensory and motor output signals only. Only the sensory noise levels have to be specified by the model designer and they are assumed to be stationary.

Besides replacing the extended with an adaptive KF, the following modifications to the model were made (Fig. 1):

1. Since, in this paper, we do not focus on inter-segmental co-ordination but on postural orientation in