Research on Improved Somatosensory Simulation Algorithm Based on VR Motion Simulator

Yuhao Jiang*
Communication university of China, Beijing 100024
*Corresponding author e-mail: gowork2018@126.com

Abstract. Aiming at the problem that the classical somatosensory simulation control algorithm used in VR (Virtual Reality) motion simulator has the shortcomings of phase delay and false hint, which leads to insufficient consistency of virtual and real motion and causes VR motion sickness, an improved somatosensory simulation algorithm is proposed. The improved somatosensory simulation algorithm adds vestibular perception system on the basis of classical simulation algorithm, feeds back the output error of the algorithm, uses fuzzy control algorithm to correct and predict the input acceleration and angular velocity, and simulates the topographic fluctuation in virtual reality. The improved somatosensory simulation algorithm is modeled and simulated in MATLAB/Simulink. The simulation results show that the improved somatosensory simulation algorithm reduces the phase delay and false hints, and improves the consistency of virtual and real motion.

1. Introduction
At present, the research of somatosensory simulation algorithm mainly focuses on three research directions: classical washout algorithm, adaptive washout algorithm and optimal washout algorithm. Nehaoua et al. [1] and Adam et al. [2] have made a comparative study of three somatosensory simulation algorithms. Finally, it is concluded that the classical washout algorithm is the most satisfactory one among the three somatosensory simulation algorithms. The classical washout algorithm has the advantages of simplicity, understandability, fast response speed and easy adjustment of parameters, but it also has some shortcomings such as false hints, phase delay, low platform utilization, etc. [3] In order to improve the authenticity of motion platform simulation, [2] used fuzzy logic controller to adjust the parameters of high-pass and low-pass filters of classical washout algorithm in real time, which improved the adaptability of the algorithm; [4] combined with variant harmonic wavelet to establish a hybrid coordinated motion simulation algorithm; [5] proposed using filter bias signal to add based on fuzzy control. Vestibular deviation signal is used to compensate the output acceleration and angular velocity signal based on fuzzy control.

Improving the consistency of virtual motion and vestibular perception can reduce VR motion sickness and improve VR experience. Considering space limitation of motion simulator, merits and demerits of somatosensory simulation algorithm and human visual-vestibular perception system, a new somatosensory simulation algorithm is proposed in this paper. The human vestibular perception model is incorporated into the algorithm, and the acceleration and constant angular velocity generated by tilt coordination are input into the vestibular system respectively. Based on the fuzzy logic
algorithm, the input acceleration is processed by using output bias. Compensation and low frequency angular velocity are transformed. Finally, VR terrain fluctuation is simulated in the algorithm.

2. Classical somatosensory simulation algorithm

So far, the research on somatosensory simulation algorithms mainly includes three directions: classical somatosensory simulation algorithm, optimal washout algorithm and adaptive washout simulation algorithm. Among them, the classical somatosensory simulation algorithm has the advantages of simple logic and short time-consuming. The quality of the optimal washout algorithm depends entirely on the accuracy of the vestibular system model, while the adaptive washout algorithm has the disadvantage of long calculation time. For VR systems requiring very short time delay and high consistency of the visual-vestibular system, compared with the complex optimal and adaptive washout algorithms, the simple classical somatosensory simulation algorithm is obviously more suitable. Therefore, we need to choose convenient and fast classical somatosensory simulation algorithm to reduce the operation time and complexity of the system.

The classical somatosensory simulation algorithm [6] includes high-pass acceleration channel, inclined coordination channel and high-pass angular velocity channel. The high-pass acceleration channel is composed of amplitude limiting link, coordinate transformation link $L_e$ such as formula (7), high-pass acceleration filter $H_{ah}$ such as formula (1) and double integral. The high-frequency part of input linear acceleration can be separated and the linear acceleration motion simulation can be carried out by VR motion simulator. The inclined coordinated channel consists of a low-pass acceleration filter $H_{al}$ such as formula (2), an inclined coordinated part. [7] The linear motion can be transformed into rotational motion by inclined coordinate. The gravity component is used to simulate the low-frequency linear acceleration, and the rotational motion can be lower than the human body sense through speed restriction. Knowing threshold is not perceived by human body. High-pass angular velocity channel is composed of amplitude limiting part, coordinate transformation link $T_s$ such as formula (4), high-pass angular velocity filter $H_{oh}$ such as formula (5) and integral. The high-frequency part of input angular velocity in VR scene can be separated, and the rotation simulation can be realized by controlling VR motion simulator.

$$H_{ah} = \frac{s^2}{s^2 + 2\xi_{ah}\omega_{ah}s + \omega_{ah}^2} \cdot \frac{s}{s + \omega_0}$$ (1)

Among them, $\xi_{ah}$ is the damping ratio of high-pass acceleration filtering, dimensionless; $\omega_{ah}$ is the cut-off frequency of high-pass acceleration filtering, unit rad/s; $\omega_0$ is the cut-off frequency, unit rad/s, value is 1.

$$H_{al} = \frac{s^2}{s^2 + 2\xi_{al}\omega_{al}s + \omega_{al}^2}$$ (2)

Among them, $\xi_{al}$ is low-pass acceleration filter damping ratio, dimensionless; $\omega_{al}$ is low-pass acceleration filter cut-off frequency, unit is rad/s.

$$H_{oh} = \frac{s^2}{s^2 + 2\xi_{oh}\omega_{oh}s + \omega_{oh}^2}$$ (3)
Among them, $\xi$ is the damping ratio of high-pass angular velocity filtering, dimensionless; $\omega_c$ is the cut-off frequency of high-pass angular velocity filtering, in the unit of rad/s.

$$L_{IS} = \begin{bmatrix} c\theta\psi & s\phi s\theta \psi - c\phi s\psi & c\phi s\theta \psi + s\phi s\psi \\ c\phi s\theta \psi & s\phi s\theta \psi + c\phi s\psi & c\phi s\theta \psi - s\phi s\psi \\ -s\theta & s\phi c\theta & c\phi c\theta \end{bmatrix}$$

(4)

$$T_s = \begin{bmatrix} 1 & s\phi t\theta & c\phi t\theta \\ 0 & c\phi & -s\phi \\ 0 & s\phi / c\theta & c\phi / c\theta \end{bmatrix}$$

(5)

3. Fuzzy logic and somatosensory simulation algorithm

3.1. Improved somatosensory simulation algorithm

The improved somatosensory simulation algorithm is shown in Figure 1. The model of human vestibular system is introduced on the basis of classical somatosensory simulation algorithm. Linear acceleration and angular velocity are directly input to the vestibular system as an output reference signal, which produces a perceptual deviation from the real motion perception signal. This kind of vestibular motion perception bias leads to the conflict between human visual signals and vestibular signals in the cerebral cortex, which leads to VR motion sickness. In order to reduce the vertigo caused by motion deviation and consider the relativity of human perception of motion, the concept of Fuzzy Set proposed by L. A. Zadeh is introduced into the control model. The perceptual bias is taken as an input of the fuzzy model. Because the classical somatosensory simulation algorithm has phase delay, the differential of linear acceleration and linear angular velocity is used as another input of fuzzy control. A new linear acceleration and linear angular velocity are input through the fuzzy control and proportional link to improve the adaptability and application breadth of the model.

VR has the characteristics of immersion and data readability, so angle compensation is added to the model to compensate for the change of gravity component caused by terrain fluctuation in VR. For high frequency motion such as collision and bump in virtual reality, it is decomposed into linear acceleration and linear angular velocity to simulate.

![Figure 1. Improved somatosensory simulation algorithm.](image)
To simulate low frequency angular velocity, the yaw angular velocity can be simulated using the gravity component in the roll direction, as shown in formula (6). All turning motions can form circular motion by finite segmentation, and the radius of motion can be judged by detecting the steering wheel and the road in VR.

Among them, the roll angle is $\varphi_{\beta\omega}$. $\omega$ is the angular velocity of turning and $r$ is the radius of circular motion formed by finite partition.

### 3.2. Fuzzy Logic Controller

Human vestibular system and visual system can only distinguish the changes of motion, but cannot make an accurate perception of motion. So in the fuzzy logic control, the input variables are fuzzified into five levels: negative large, negative small, medium, positive small, and positive large, which are expressed by letters VN, N, Z, P, and VP respectively.

The membership function of input angular velocity error is shown in formula (7) and its figure is shown in Figure 2 (a). The membership function figure of input acceleration error is shown in Fig. 2 (b), the membership function figure of input acceleration and angular velocity differential is shown in Fig. 2 (c), and the fuzzy output membership function figure of translation and rotation is shown in Fig. 2 (d).

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\begin{align*}
\mu_{yN}(x; 5, 3) &= \max(\min(-x - 3/2, 0), 0) \\
\mu_{yN}(x; 5, 3, -1) &= \max(\min(x + 3/2, 0), 0) \\
\mu_{y}(x; 2, 0, 2) &= \max(\min(x + 2/2, 0), 0) \\
\mu_{x}(x; 1, 3, 5) &= \max(\min(-x + 1/2, 0), 0) \\
\mu_{y}(x; 3, 5) &= \max(\min(-x - 3/2, 0), 0)
\end{align*}
\]

The fuzzy control table is shown in Table 1. Its fuzzy rules are as follows: when the output error is negative and the input change rate is negative, it shows that the output error is large and the input error is decreasing rapidly and the output error is increasing, so the change of control quantity should be negative as soon as possible; when the output error is negative and the input change rate is positive, it shows that the error is decreasing, so as to avoid overshoot. The change of time control is in the middle.

### 4. Simulation results and analysis

This paper uses MATLAB/Simulink to verify the stability and reliability of the improved somatosensory simulation algorithm. A step acceleration signal with amplitude of 3m/s^2 is used in the simulation model. The acceleration signal mutates to 3m/s^2 at 1s and 0m/s^2 at 7s.
Fig. 3 (a) is a human sensory acceleration curve, which shows the reference curve (human vestibular sensation curve), classical curve (classical somatosensory simulation algorithm curve) and improved curve (improved somatosensory simulation algorithm curve) under the input of 3m/s² step signal. The human vestibular perception curve is a response curve that directly inputs the acceleration and angular velocity signals in VR scene into the human vestibular model. It is used as a standard perception curve and is named as a reference curve in Figure 3. The classical curve is to input the acceleration and angular velocity signals in the VR scene directly into the classical somatosensory simulation algorithm to process the signals for the VR motion simulator and then pass through the response curve of the vestibular system model for comparative analysis with the reference curve. The improved curve is to input the acceleration and angular velocity signals in VR scene directly into the improved somatosensory simulation algorithm to generate the signals needed for the control of VR motion simulator, and then input the signals from the improved somatosensory simulation algorithm into the vestibular system model to obtain the improved curve, which is compared with the reference curve and the classical curve. The improved curve directly shows that the amplitude of the classical curve is close to the reference curve in Fig. 3 (a), but there is a delay of 2S in phase, which results in the sensory acceleration error of 0.8m/s² as shown in Fig. 3 (b), thus generating false hints in actual motion perception. The improved somatosensory simulation algorithm achieves a good tracking of the reference curve in phase when the amplitude is close to each other, and overcomes the shortcomings of the classical somatosensory simulation algorithm such as false hints and phase delay. Synchronization of motion perception and visual perception can better reduce motion sickness caused by VR.
Figure 3. Stepped signal response curve.

Figure 4. White noise response curve.

The displacement curves of classical somatosensory simulation algorithm and improved somatosensory simulation algorithm are shown in Fig. 3 (d). It can be seen that the displacement of classical phantom simulation algorithm is 0.21, and that of improved phantom simulation algorithm is 0.38. Compared with the classical somatosensory simulation algorithm, the improved somatosensory simulation algorithm improves the platform utilization by 80.9%. The response curves of classical somatosensory simulation algorithm and improved somatosensory simulation algorithm are shown in Fig. 4. The sensory acceleration is shown in Fig. 4 (a) and the absolute error of sensory acceleration is shown in Fig. 4 (b). The RMS of classical somatosensory simulation is 0.1077, the RMS of improved somatosensory simulation is 0.0071, and the root mean square error is changed from 0.1077 to 0.0071. This indicates that the improved somatosensory simulation algorithm has better human perception effect than the classical somatosensory simulation algorithm. Somatosensory simulation algorithm has higher platform utilization ratio than the classical somatosensory simulation algorithm.

5. Conclusion

Somatosensory simulation algorithm is to simulate virtual motion in VR scene by using six-degree-of-freedom VR motion simulator. The quality of somatosensory simulation algorithm directly affects the accuracy of simulation motion. The human vestibular system is introduced into classical
somatosensory simulation algorithm. Fuzzy control is used to control input and somatosensory error feedback, which reduces the phase delay and false hints in classical somatosensory simulation algorithm, improves the authenticity and stability of motion perception, and reduces the perceptual bias of vision and vestibule in VR human-computer interaction. Compared with the classical somatosensory simulation algorithm, the improved somatosensory simulation algorithm improves the motion accuracy of VR motion simulator, makes the virtual motion of VR received by visual nerve consistent with the actual motion of VR motion simulator received by vestibule, and reduces the VR vertigo caused by the perceptual conflict of visual-vestibular system. However, the improved somatosensory simulation still has a small error at the vertex, which leads to the inability to completely eliminate the VR vertigo caused by the visual-vestibular system perception conflict, which will be studied in the future.

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