Multi-Sensory Consistency Experience: a 6DOF Motion System Based on Video Automatically Generated Motion Simulation

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Abstract. As we perceive our surroundings in the real world through the integration of multiple senses, the experience of perceiving consistency through multiple senses in a virtual environment may enhance our presence. In this paper, we present a multi-sensory perception consistent 6-DOF motion system. The system automatically extracts the motion trajectory of the virtual camera as motion data from video and maps the motion data to the 6-DOF Stewart motion platform through a human perception-based wash-out algorithm and incorporates multi-sensory simulations of visual, auditory, tactile, and proprioceptive sensory perceptual consistency of the motion effect. The results of the user study showed that the system effectively enhanced the participants' sense of realism and reduced the subjective perception of simulator discomfort. In addition, the system well supported users to self-create motion virtual environment through video, so that the public became the designer of motion experience content in the metaverse.

Keywords: Multi-sensory consistency · Virtual reality · Motion platform · Simulation experience.

1 Introduction

With the advancements in virtual reality and interactive technology, the use of motion seats in 3D cinema [44], digital cultural tourism [36], and driving simulation [46] is becoming increasingly widespread. The motion platform with seats integrates multiple sensory modalities, such as vestibular motion, tactile vibration, olfactory senses, and wind to enhance the immersion and realism of the simulation experience.

The motion seat system is a key element to achieve the "immersive" effect [27], which allows the audience to be more deeply integrated into the movie plot. Many studies have constructed dynamic simulation experience systems [25, 1] using computer-generated virtual scenes on the Stewart [14, 41] six-degree-of-freedom (6-DOF) dynamic seat. However, CG virtual scenes require professional modelers to build and design the scene, set specific driving routes, and simulate motion data. It leads to a lack of realism in CG virtual scenes, and they do not support ordinary users to create, resulting in limited experience content and slow scene updates. With the development of multimedia technology, video has become a popular form of visual presentation. Traditional video-based dynamic data generation methods mainly include manual or rocker methods [7]. As the lens changes, the expert manually makes the motion parameters corresponding to the dynamic seat in a single frame according to their own inner experiences and feelings. In the rocker method, the expert holds a joystick and shakes it while viewing, using a measuring device to track its movement and generate dynamic data. However, the above methods require professional experts to operate, which is labor-intensive, inefficient, and costly. Additionally, there are subjective factors in obtaining motion data.

To reduce the difficulty of creating motion virtual environment and improve user experience, this paper proposed a multisensory consistent simulation experience system based on the 6-DOF motion platform. The system supports users to import self-captured videos as virtual scenes. Then, with the video frame image and camera parameter data as input, the ORB-SLAM3 system is used to obtain the global motion pose of the virtual camera in the video to automatically generate motion data. The system is based on 6-DOF dynamic seats, three-screen parallel display devices, audio and fan, and other immersion enhancement devices, providing users with a multi-sensory perceptual consistency of visual, auditory, skin, proprioceptive and other immersive experience. Based on this method, we constructed simulated scenes in the form of video and CG-virtual scenes for comparative experiments. The results show that our system has better usability and brings a more realistic experience to users.

In summary, the contributions are as follows:

(1) Universal motion data extraction and virtual scene production. Users can easily create motion simulation experiences by uploading videos, empowering everyone to become a creator of virtual environments.

(2) Integrated multi-sensory perceptual consistency for an immersive experience. The system provided users with a multi-sensory perceptual consistency of visual, auditory, skin, proprioceptive and other immersive experiences based on a 6-DOF motion platform.

(3) Constructed 6-DOF motion platform simulation scene according to video automatic generating motion data and CG-virtual scene with manual making motion data for the user study.

2 Related Work

2.1 Simulation Experience System on Motion Platform

Dynamic cinema integrates visual, auditory, olfactory, tactile, and motion senses perfectly. However, the development of dynamic movies is limited due to slow content updates and low repeat visit rates [21]. Imgeun and Lee developed a video-based motion effect generation system [26]. The system uses the light stream generated by the video image to create instantaneous motion effects, giving the user a dynamic experience of motion impact. Shi et al.[37] proposed a video-based motion effect automatic generation framework, which relies on Boujou to estimate the 3D trajectory of the camera in the world coordinate frame. Then, the pose of the camera is numerically differentiated once and twice to obtain angular velocity and linear acceleration. These variables are sent to the classic washout filter to create motion commands for the motion seat. It makes it possible to automatically create dynamic virtual scenes using video. Lee et al.[27] used optical flow to find corresponding points between two consecutive frames and used epipolar constraints to estimate the relative camera motion between adjacent frames.

2.2 Motion Simulation of 6-DOF Stewart Platform

The 6-DOF Stewart platform is a motion simulation technology mainly used to achieve a sense of motion in a limited range of motion to simulate a real environment[29, 39, 38]. The most common approach currently used is to use a washout filter to transform the actual motion of the virtual camera into a signal that can be perceived similarly by humans and can be implemented by the simulator [3].

Many studies on adjusting washout filters [3, 32, 31, 30, 10, 12] have been successfully applied to motion simulators such as flight simulators and car simulators, greatly improving the sense of reality. Currently, there are three main types of motion algorithms used in six-degree-of-freedom simulators: classical washout algorithm, optimal washout algorithm, and adaptive washout algorithm. The classical washout algorithm [31, 30, 10] uses high-pass and low-pass filters to solve the problem of the limited motion range of the simulation platform. It is highly praised by experts for its simple structure, easy adjustment, fast execution speed, and quick feedback. However, the structure and parameters of this algorithm are fixed and cannot be automatically adjusted according to changing input signals, which limits its practical application. Mohammad et al. [33] proposed the optimal washout algorithm, which uses mathematical optimal control theory to select the form of the filter and introduces the human vestibular model to reduce the distortion of the user's perception. Based on the optimal washout algorithm, Houshyar et al. [2] proposed an improved adaptive washout algorithm that uses optimized fuzzy control systems to solve the drawbacks associated with the existing optimal MCAs of the motion simulators. The method can adjust the parameters of the algorithm in real time according to the motion state of the platform and adjust the filter with the optimal control method.

2.3 Multi-sensory Consistent Design

Objective and subjective measures of performance in virtual reality environments increase as more sensory cues are delivered and as simulation fidelity increases [11, 9]. The study on multisensory stimulation has shown that presenting visual and auditory sensory cues alone or in combination can improve target localization [23] and task performance in spatial attention tasks [22], without affecting the perceived workload.

The multisensory experience [40, 15, 18, 16] combines various stimuli such as visual, auditory, olfactory, and proprioceptive senses to integrate the information received from each sense, allowing users to perceive product or system information in a comprehensive and multi-layered way, resulting in a more complete and enriched experience [28]. Nimesha et al. [34] presented Season Traveller, a multisensory VR narration of a journey through four seasons within a mystical realm. By adding olfactory and tactile stimuli, the traditional audio-visual VR technology was expanded to achieve a multisensory interactive experience. Mi et al. [17] proposed that multisensory feedback in virtual environments can improve user experience and performance when studying the tactile experience in a walking immersive virtual environment. Kaliuzhna et al. [24] studied the simultaneous interaction between visual, tactile, and vestibular senses and proposed a layered multisensory interaction method that supports proprioceptive modulation. These studies demonstrate that human centered interaction design, considering multisensory interaction, is crucial in various fields.

3 Multi-sensory 6-DOF Motion Platform Simulation System Design and Implementation

The system consists of a motion data generation module, motion simulation module, and multi-sensory perception consistency design, as shown in Fig 1. Users can upload video content captured with a regular or panoramic camera to the motion platform. The motion data generation module extracts 6-DOF global camera pose data from the video, which is then smoothed using an interpolation algorithm to drive the dynamic seat. The motion simulation module maps the generated motion data to the dynamic seat's range using a washout algorithm, enabling motion control. The multi-sensory perception consistency design enhances the users' realistic and immersive experience on the 6-DOF motion platform.

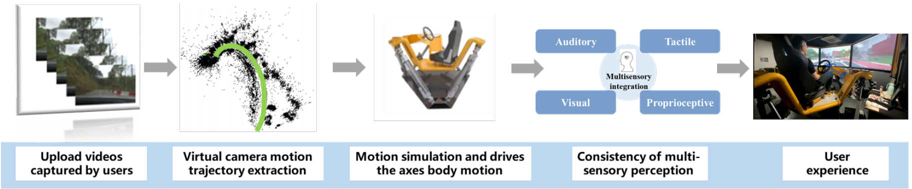


Fig. 1. Multi-sensory 6-DOF motion platform simulation system

3.1 Motion Data Generation Module

The system processes the video uploaded by the user and automatically generates motion data, providing seat-driving data for the motion simulation module, reducing the manual cost of dynamic experience design. To ensure the consistency and smoothness of video playback and seat motion, we uniformly adjust the video frame rate to 30fps and generate a timestamp file corresponding to video frames. Then, the system takes the video frame and camera parameters as input, and extracts the global 6-DOF motion pose of the camera in videos based on the ORB-SLAM3 framework [8], as shown in Fig 2.

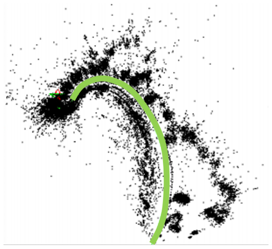
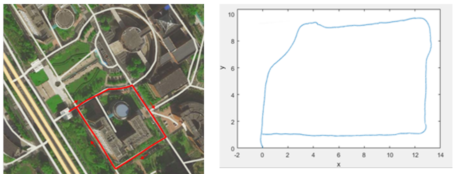


Fig. 2. Camera motion trajectory diagram (green line)



(a) Satellite map of the video path

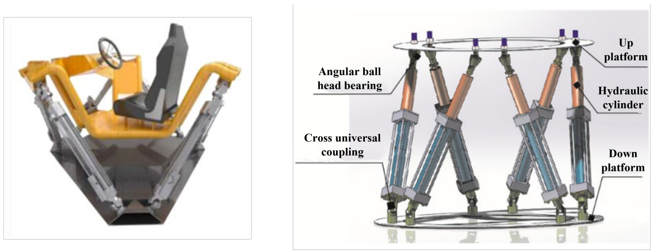
(b) The camera motion trajectory extracted based on ORB-SLAM3

Fig. 3. Comparison of satellite map and camera position

Each frame in the video corresponds to the global pose data of the camera motion[timestamp, t_x, t_y, t_z, q_1, q_2, q_3, q_w]. The t_x, t_y, t_z represent the position of the current frame. The q_1, q_2, q_3, q_w are Quaternions of rotation, so the Q=q_1*i+q_2*j+q_3*k+q_w is representing the camera rotation posture of the current frame. Fig 3 shows a comparison between the satellite map of the panoramic video path we captured and the camera pose trajectory extracted based on ORB-SLAM3.

3.2 Motion Simulation Module

The motion simulation of this system is achieved by using a 6-DOF Stewart motion platform [41] and a three-screen parallel vision system, as shown in Fig 4. In this system, the proprioception simulation [19] mainly performs the global motion of the virtual camera in the video. The motion platform can apply acceleration and force to the user, matching the visual content, thereby achieving the function of dynamic simulation. The camera posture data needs to be be



(a) Motion seat overall structure

(b) Stewart Platform structure

Fig. 4. Motion seat structure in our system

converted into angular velocity and linear acceleration signals based on human perception factors [42]. Then, the kinematic inverse solution of the Stewart platform model is calculated to obtain the data of each axis of the seat length, which is input to the seat control program to manipulate the motion of the platform.

The main functions of the motion simulation module include:

(1) Camera motion simulation. Firstly, the interpolated and smoothed camera pose data (virtual camera pose data) is converted into linear acceleration and angular velocity. And a human perception-based washout algorithm [43] is used to generate the 6-DOF motion platform pose command. Then, the kinematic inverse solution is used to obtain the driving signals of each branch to control the motion of each hydraulic cylinder. The entire process is shown in Fig 5.

(2) Motion seat drive control. The system communicates with the seat control program of the motion platform to drive the seat motion in real-time. As the sending end, the system needs to establish a request data packet to connect with the seat-driving program. After the connection is successful, message transmission can be performed. On the seat driving program side, the Receiver Class is created to receive various commands and drive the seat motion. The functional class diagram of this part is shown in Fig 6.

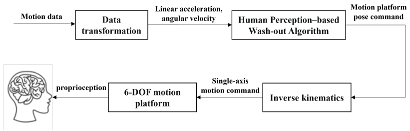


Fig. 5. Motion simulation process

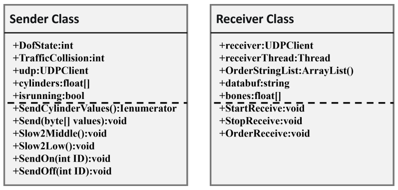


Fig. 6. Functional class diagram

3.3 Consistent Design for Multi-sensory Perception

Multisensory perceptual consistency refers to the spatial, temporal and motor consistency of multiple senses, which is an effective guarantee of natural and comfortable human-computer interaction [28]. In this system, users can obtain multi-sensory perceptual consistency of visual, auditory, tactile, and proprioception senses during motion experience. The analysis of multi-sensory perception is shown in Fig 7.

The system ensures audio-visual consistency by addressing synchronization and parallelism issues during video pre-processing. Synchronization maintains a natural relationship between sound and image, while parallelism aligns the audio closely with the video content, enhancing emotional expression.

Additionally, the system ensures that motion data processing aligns with video playback frames. Developed using Unity 3D with FixedUpdate(), the system processes motion data per fixed frame update, ensuring a consistent correspondence between video frames and motion data rows. This is achieved by equating the camera pose data, denoted as N_1, with the number of video frames, denoted as N_2, resulting in the equation $N_1 = N_2$. Assuming the duration of

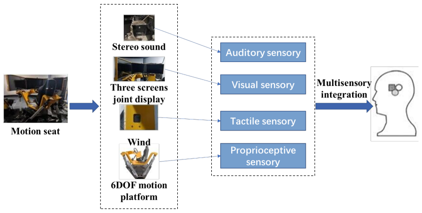
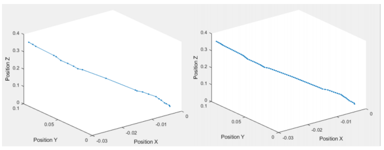
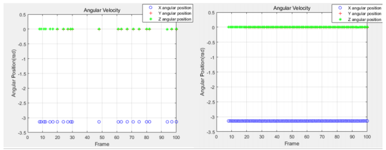


Fig. 7. Multisensory integration design



(a) Position data before interpolation (b) Position data after interpolation



(c) Euler Angle data before interpolation (d) Euler Angle data after interpolation

Fig. 8. Comparison of the spatial distribution of posture and the Euler angles before and after interpolation.

video playback and seat movement is t, the mathematical model for visual and proprioception consistency can be represented as $N_1 = N_2 = t * fps$.

As the system is implemented based on the Unity engine to map camera motion to various branch control signals, the interpolation of camera pose data needs to follow the data smoothing characteristics of Unity. Vector3Lerp(Vector3 a, Vector3 b, float t) and QuaternionLerp(Quaternion a, Quaternion b, float t) are used to implement the motion pose and attitude quaternion of the camera. Where a is the initial value, b is the end value, and t is the deciding factor for inserting values between a and b. Assuming the target value is r, it satisfies the following formula: $r = a + (b - a) * t$, where $t = 1/(b_n - a_n + 1)$, a_n represents the frame number where the initial value is located, and b_n represents the frame number where the end value is located. Taking the "Pacific Coastal Highway" video under the "City Car Travel" type in the system as an example, the camera pose data obtained is interpolated based on this model, and the data of 8-100 frames is shown in Fig 8. Additionally, we synchronized fan speed with camera movement to match blowing sensation.

4 Evaluations

Compared to traditional CG-virtual scenes, video-based virtual scenes offer users a more realistic experience [13]. Studies have shown that in virtual reality environments, incorporating more sensory cues and improving simulation fidelity enhances both objective and subjective performance indicators [11]. This experiment aims to investigate whether a 6-DOF motion platform generated with video-based content and automated motion data offers a superior multisensory consistency experience compared to one based on 3D modeling and manual motion data making.

4.1 Hypothesis

Based on the advantages of multisensory consistency experience on the 6-DOF motion platform, we hope that generating a multisensory perceptual consistency dynamic simulation experience based on video can provide a superior user experience and user performance compared to the manually drawn dynamic simulation based on CG-virtual scenes. Therefore, we propose the following hypothesis: Participants rate the multisensory consistency experience higher on the 6-DOF motion platform using video generation compared to CG-virtual scenes with manually created single frame dynamic data.

4.2 Participants

Our participants were 30 adults, 14 females and 16 males, with ages ranging from 18 to 28 years (M= 24.73 years, SD=2.94 years). They were undergraduate and graduate students recruited on campus who were interested in the study. None of the participants had known audiovisual behavior or sensory disturbances, and none were known to have significant 3D vertigo. They received a gift of appreciation after the experiment.

4.3 Experimental Design

The user study employed a single-factor within-subject experimental design. The within-subject factor was two types of dynamic sensory experience scenes: a simulation experience system with video as the presentation content and a dynamic sensory experience system with 3D modeling as the presentation content. Other factors, except for the presentation content and the method of generating dynamic data, were kept consistent between the two conditions. The dependent variables included realism, immersion, fatigue, motion sickness, consistency, comprehensibility, misdirection, and personal preference.

4.4 Experimental Environment and Task

The experimental environment consists of two systems: a multi-sensory consistency simulation experience motion system generated based on video (called Video-auto) and a CG-virtual scene with a manual making data motion system (called CG-manual). Both systems are experienced on a 6-DOF motion platform. The Video-auto system presents low-cost videos as the presentation content and automatically generates driving paths for users by extracting camera movements from the videos, providing corresponding dynamic sensory experiences. The CG-manual system built using 3D modeling presents technical expert virtual scenes as the presentation content and provides users with corresponding dynamic sensory experiences by pre-setting paths manually. This user study aims to validate the usability of our proposed method and its ability to provide users with more realistic multisensory consistency experiences.

To reduce the impact of novelty bias [45] caused by inconsistent content (which usually occurs as positive decision bias in novel experiences), the two systems' experience scenes were both "mountain road" driving types, as shown in Fig 9. Participants were free to decide the order in which they experienced the two scenes, with each scene experienced for 20 minutes, resulting in a total experiment duration of 40 minutes. To reduce fatigue and prevent motion sickness, participants were required to rest for at least 5 minutes after experiencing one scene before experiencing the other. After each scene experience, participants were required to complete a corresponding questionnaire.

The hardware used in the experiment is a 6-DOF motion seat with a Stewart platform, as shown in Fig 10. The multisensory consistency experience system on the 6-DOF motion platform based on video generation is developed using Unity 2018.4.15f1 and runs on a 64-bit Windows 10 Professional Edition.

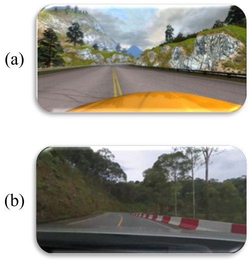


Fig. 9. Visual scene comparison in experiment.(a) CG-manual scene (b) Video-auto scene

Fig. 10. Panoramic video generation for 6-DOF dynamic platform multisensory consistent experience.

4.5 Measurement

(1) Evaluation of system usability. We employed the PSSUQ V3.0 (Post-Study System Usability Questionnaire) to assess the availability of our system.To determine the usability of the system, we compared the obtained scores with the reference scores. If the score surpassed the reference score, we considered it to have good usability. The reliability of the scale (Cronbach's $\alpha = 0.8642$) in this study is good.

Table 1. Evaluation of user experience

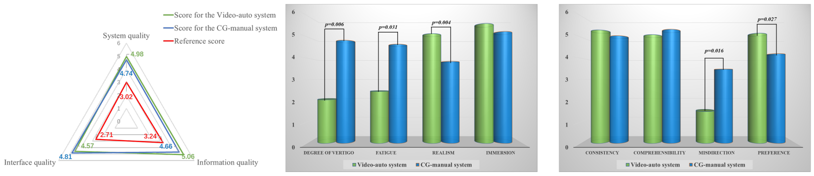
Evaluation Metrics	Item Description
Degree of vertigo	Refer to Simulator Sickness Questionnaire [6].
Fatigue	After the experience, I felt very tired.
Realism	I felt as if I was actually in a driving car.
Immersion	Refer to Flow experience [35].
Consistency	Audio-visual information as well as haptic feedback (wind) are matched to the motion effect.
Comprehensibility	I can understand the relationship between audio-visual information and motion effects.
Misdirection	There are motion effects that I don't understand why should be provided.
Preference	I like motion simulation that automatically generates motion data based on video.

(2) Evaluation of user experience.The content of the user experience evaluation questionnaire is shown in Table 1. Questions Q1-Q4 evaluate the user's overall dynamic sensory experience, while questions Q5-Q8 evaluate the quality of the dynamic sensory effects. The questionnaire design was based on the study by Yun et al. [45], and questions were designed to assess aspects such as realism, immersion [35], motion sickness [6], fatigue, consistency, comprehensibility, misdirection, and personal preference. The answer options were designed using

a 7-point Likert scale, and the reliability of the scale (Cronbach's $\alpha = 0.8201$) in this study is good.

4.6 Results

(1) System usability analysis. The average scores for system satisfaction are shown in Fig 11. The analysis results indicate that the system scored higher than the reference scores in terms of usability, information quality, and user interface quality, indicating that the system has good usability.



(a) Comparison of system usability scores (b) The motion experience of the user (c) The quality evaluation of motion effect

Fig. 11. Score comparison of users' evaluation

(2) User Experience analysis.To investigate the differences in various indicators between participants using two types of systems for immersive experiences, we used the Shapiro-Wilk test to check the normality of the data, and the results showed that all data in this study were normally distributed. Therefore, we conducted a paired-sample t-test on the questionnaire data, and the descriptive statistics and testing results are shown in Fig 11 . The analysis results indicate that there are significant differences between the two systems in terms of SSQ, fatigue, and realism scores in the evaluation of immersive experiences (Q1-Q4) (t=0.462, p=0.006; t=2.943, p=0.031; t=4.951, p=0.004). Our Video-auto system provides users with a more realistic experience and reduces the occurrence of motion sickness and fatigue compared to the CG-manual system. However, there is no significant difference between the two systems in terms of immersion scores (t=1.649, p=0.513). In terms of the quality evaluation of immersive effects (Q5-Q8), there is no significant difference between the two systems in terms of consistency and comprehensibility scores (t=2.461, p=0.183; t=1.607, p=0.116). However, there are significant differences in terms of misleadingness and personal preferences (t=2.455, p=0.016; t=1.449, p=0.027).

5 Discussion

In this study, we present a system that enhances multi-sensory perception consistency using a video-generated 6-DOF motion platform. The system simulates the user's perspective by extracting motion data from the global 6-DOF motion pose of the virtual camera in the video. This data is then optimized and mapped to the motion platform's axes using a perception-based algorithm. Users can import their own videos and experience multi-sensory immersion, including visual, auditory, tactile (wind), and proprioceptive feedback through the 6-DOF Stewart platform seat. To evaluate our system, we conducted a user study comparing it to a computer-generated virtual scene with manually created motion data. The results demonstrate that our system provides users with a more realistic and consistent multi-sensory perception experience.

In terms of motion experience, our system and the CG-Virtual Scene with manual making-based system both provide good immersive feedback. However, based on the SSQ and fatigue scores, the motion experience system based on CG-Virtual Scene with manual making seems to be more likely to bring unpleasant experiences to users. This is consistent with previous research [20], which suggests that conflicts between platform motion and visual performance can cause motion sickness and poor virtual experiences. In contrast, the video-generated 6-DOF motion platform largely ensures multi-sensory perception consistency experience, reducing SSQ and fatigue to some extent. The CG-Virtual Scene with manual making-based motion experience system also suggests that simply adding additional sensory stimulation may have a negative impact on users [4, 5], as it can bring the additional cognitive load to users and make them feel overwhelmed and distracted in the virtual environment, especially when multi-sensory information is inconsistent.

It is worth noting that although there is no significant difference in the average consistency scores between our system and the CG-Virtual Scene with the manual making-based system, our system still has a slightly higher average score. In terms of personal preferences, most participants prefer our system, largely because the video-based motion experience can provide them with a stronger sense of reality.

In addition, our work also has some limitations. The video-generated 6-DOF motion platform multi-sensory perception consistency experience system currently mainly integrates visual, auditory, tactile (wind), and proprioceptive perception, while olfactory and gustatory perceptions have not been fully developed, which can bring significant value to many applications in VR. In future work, we will continue to explore multi-sensory perception consistency experience and design participatory user research from shooting to motion experience (autonomous creation of experience content).

6 Conclusion

We proposed a system that combines video-generated 6-DOF motion platform technology with multi-sensory perception consistency. The system captures motion footage using a motion camera, extracts motion trajectory data from the virtual camera, and maps it to the 6-DOF Stewart motion platform using a perception-based washing algorithm. An experimental study was conducted to evaluate the usability and user experience of the system. The results demonstrate that our proposed system offers users a more realistic motion experience while incorporating multiple senses such as visual, auditory, tactile (wind), and proprioceptive feedback. Additionally, it reduces the likelihood of motion sickness and fatigue in virtual reality. The system provides a convenient and efficient approach for designing 6-DOF motion experience content, enabling ordinary users to contribute to motion experience content creation through video shooting.

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