RHapTor: Rendering Haptic Torques for Virtual Reality

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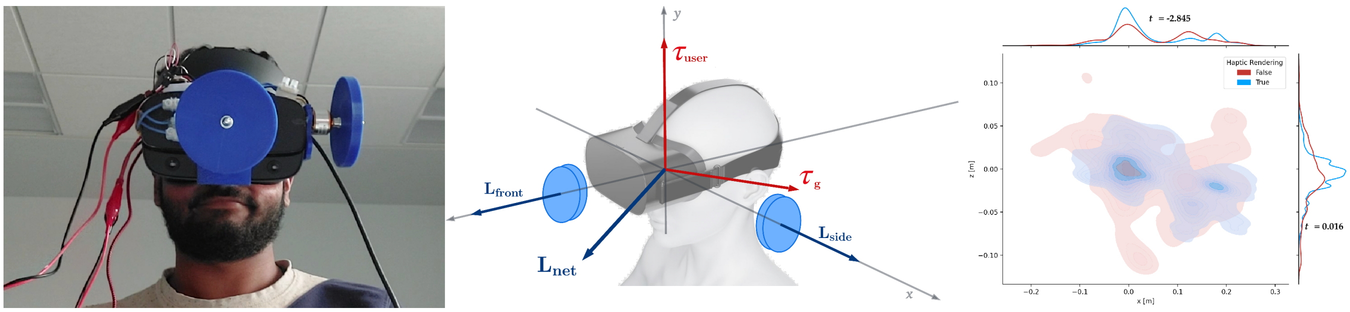

Figure 1: The RHapTor device (left). An example gyroscopic torque,τ_g , generated by head rotation while disks spin (middle). User exploration profile in the x-z plane, for a virtual beach environment with and without resistive torque rendering, with t-values describing the difference in means between each pair of univariate distributions (right).

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1 INTRODUCTION & RELATED WORK

This work investigates the use of rotational inertia from gyroscopic torques as a means of haptic feedback to augment Virtual Reality (VR) experiences. While modern VR systems are capable of fabricating visual and auditory immersion into alternate realities much better than the technologies from a couple decades ago, studies have long shown that forms of haptic engagement can effectively enrich this experience and be used as a means of communication [Brewster et al. 2005]. It is no surprise that after VR's success with audio-visual modalities, haptics are the natural next step.

Kinaesthetic haptics are a subset of haptic feedback modalities that rely on mechanoreceptors in the muscle tendons to detect information regarding resistance and tension [Yen-Yi et al. 2020]. The phenomena of resistance and inertia are central to the perception of kinaesthetic haptics by the nervous system, and their manipulation is required to make any progress in kinaesthetic immersion in VR. We exploit rotational inertia from gyroscopic torques as a means of haptic feedback to augment the VR experience. Gyroscopic torques are induced in any situation when an external torque is applied to an object already spinning, and can be felt as a form of resistance. In our case, the user turning their head while a disc is spun on the head-mounted display (HMD) generates a resistive torque.

Previous work in this area such as *GyroVR* [Gugenheimer et al. 2016], *Kabuto* [Tanichi et al. 2020] and *Odin's Helmet* [Hoppe et al. 2021] show a consistent trend of building upon each other's scope of gyroscopic feedback through hardware advancements with more motors and electrical components, but no extensive research or development has been done on software control and functionality. Current software frameworks for haptic rendering in the literature are lacking sophisticated torque rendering capabilities.

In this work, we present 3 torque manipulation algorithms for a variety of haptic effects from a relatively simple hardware implementation. We propose and implement *RHapTor*, a hardware/software prototype that tackles the disparity between audio-visual and haptic engagement. We developed a haptic rendering device mounted onto an Oculus Rift S that uses a two-axis motor system to manipulate inertia. Sophisticated algorithmic control of gyroscopic torques allow both vibrational and kinaesthetic feedback in VR.

Our solution is inspired by the findings of Gugenheimer et al.'s *GyroVR*, which was the first to exploit the perception of gyroscopic torques on the head as a rendering stimulus [Gugenheimer et al. 2016]. We build on their work with recent advancements in the field and an investigation into the optimal hardware and software parameters that truely enhance VR experiences.

2 IMPLEMENTATION

Hardware. We employed two 2200 KV brushless DC motors (BLDCs) on a 3D printed mount, controlled by an Electronic Speed Controller (ESC) connected to an Arduino Nano microcontroller. The motors are mounted at right angles to facilitate a range of torque vectors for rendering haptic feedback. Our implementation weighs 1040 g (81% higher than an unmodified Oculus Rift S), and

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Figure 2: Left to Right: Beach, Museum and Rocky Planet environments used in a preliminary study of our haptic rendering modes. Open source skyboxes taken from OpenGameArt.Org [Creative Commons Licence] (https://opengameart.org/users/tapio)

its dual motor system generates net torques up to 0.23 Nm, with a peak noise level of 73.1 dB. The angular momentum associated with a spinning disk is directly related to the angular velocity of the disc. By the rotational analogue of Newton's second law, we are able to relate the time-dependent torque imparted by each BLDC, $\boldsymbol{\tau}(t)$, to the change in angular momentum of the disc,

$$\Delta \mathbf{L} = \int_{t_1}^{t_2} \boldsymbol{\tau}(t) \mathrm{d}t. \quad (1)$$

Fig 1 (middle) shows the interaction of the angular momenta of our two discs, induced by time-dependent torques controlled by our rendering algorithm. The external torque of the user's head rotation, with angular velocity $\boldsymbol{\omega}_{\text{user}}$, is the cause of the gyroscopic torque, $\boldsymbol{\tau}_{\text{g}}$, rendered throughout this work:

$$\boldsymbol{\tau}_{\text{g}} = \boldsymbol{\omega}_{\text{user}} \times \mathbf{L}_{\text{net}} = \boldsymbol{\omega}_{\text{user}} \times (I_{\text{front}} \boldsymbol{\omega}_{\text{front}} + I_{\text{side}} \boldsymbol{\omega}_{\text{side}}). \quad (2)$$

Our actuation concept exploits the vestibular system as a sensation interface. It relies on gyroscopic torques to impede motion, stimulating the otolith organ to perceive a different rotation from the expected one, based on the torque from the neck muscles. The otolith organ registers a stimulus that matches the auditory and visual stimuli rendered to the ears and eyes.

Software. We treat *RHapTor* as a Finite State Machine (FSM). We introduce 3 different algorithms that generate different sensations, along with three environments to showcase these effects (Fig 2).

(1) *Resistance* rendering mode involves setting the motor to spin at a constant angular velocity, i.e., $\mathbf{L}_{\text{net}}$ from Equ 2 does not change. Which is to say the FSM remains in the same state for the duration of the experience and the resistance from a constant $\boldsymbol{\tau}_{\text{g}}$ has interesting use cases, e.g., simulating wind resistance in the *Beach* environment.

(2) *Dynamic Tension* increases the output torque when the user displaces their head from the z-axis at a rate greater than a fixed threshold, ω_{thresh}. Angular velocity was chosen in favour of angular displacement to make rendering meaningful in free navigation. In our user study, this was motivated by guidance systems and worked well in guiding user's gaze to artefacts in the *Museum* environment.

(3) *Rumbling* rendering modes. We devised two rumbling effects that our architecture lends itself to naturally. The first is a 'directional' rumble, created when the angular momentum of each disc oscillates between a low and a high value with a phase difference of 180°, to shake the net $\boldsymbol{\tau}_{\text{g}}$ direction. The second effect is a 'magnitude' rumble, where the discs raise and lower their angular momenta in sync, thereby varying $|\mathbf{L}_{\text{net}}|$ and again consequently, $\boldsymbol{\tau}_{\text{g}}$ (by Equ 2). This is perceived by the vestibular system as a variation in rotational inertia of the head. This mode renders both kinaesthetic and vibrational feedback, with falling rocks and meteor events triggering state changes in the *Rocky Planet* environment.

3 RESULTS AND CONCLUSION

We measured the perceived effect of our torque generation techniques through a preliminary user study. We were able to render perceivable torques in the majority of trials. The preliminary study indicated that haptic rendering has a noticeable and statistically significant effect on a user's perception of a virtual environment, and can even be used to guide a user's visual attention. Fig 1 (right) shows users' exploration profile in the x-z plane (y translations were negligible), exploring the *Beach* environment with and without resistive torques rendered. Rendering *resistance* directed head movement and caused a shift in the exploration profile to a lower spread in z-axis motion, even shifting the mean x-axis motion as shown by the independent two-sample t-test with $t = -2.485$.

The rendering of other modes remains challenging. ESC limitations prevent us from making more complex and intricate torque variations that match the resolution of human gyroscopic torque sensitivity. Future works would look into increasing the quality of immersion into environments that rely on gyroscopic torque variations, such as guided virtual tours with dynamic tension rendering.

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