GyroTab: A Handheld Device that Provides Reactive Torque Feedback

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ABSTRACT

Haptic devices that provide robust and realistic force feedback are generally grounded to counterweight the applied force, prohibiting their use in mobile devices. Many ungrounded force-feedback devices rely on the gyro effect to produce torques on the human body, but their active control systems render them extremely bulky for implementation in small mobile devices. We present GyroTab, a relatively flat handheld system that utilizes the gyro effect to provide torque feedback. GyroTab relies on the user to produce an input torque and provides feedback by opposing that torque, making its feedback *reactive* to the user's motion. We describe the implementation of GyroTab, discuss the kinds of feedback it generates, and explore some of the psychophysical results we obtained from a study with the device.

Author Keywords

Haptics; gyroscopic feedback

ACM Classification Keywords

H.5.2. [Information interfaces and presentation]: User Interfaces – Haptic I/O.

General Terms

Algorithms, Design, Human Factors.

INTRODUCTION

With the drive to enhance user experiences on general-purpose mobile devices, there is a growing trend to go beyond visual and auditory sensory channels, in particular to engage the sense of touch with haptic feedback. The most common type of haptic feedback is vibrotactile feedback, which uses vibrations or small surface changes to provide feedback. Although vibrotactile devices have been widely deployed in mobile phones and game controllers, they tend to be relatively weak and cannot actively convey forces. On the other hand, kinesthetic feedback, such as that generated by devices like the Phantom haptic device [4], actively replicates real-world forces and has been previously used to simulate large, rigid, and deformable objects. This feedback can be much stronger than that provided by vibrotactile feedback, but the vast majority of kinesthetic feedback devices rely on *grounding*: the physical attachment of the device to the ground or a large surface to act as a counterbalance for the forces it exerts.

Figure 1: GyroTab provides reactive torque feedback. Two masses (under the display) spinning in opposite directions are controlled to produce varying levels of feedback that oppose the user's movement.

In this work, we set out to create a kinesthetic force feedback device that we envision integrating into a practical mobile form factor. In order to create a flat system, we built a device that produces *reactive* feedback instead of actively generating torque. In this way the movement of the user acts as the input torque for the gyroscopes and no feedback is produced unless the user is moving. We call this device GyroTab (Figure 1). GyroTab consists of (1) a pair of flat, disk-shaped masses that are spun in opposite directions to create an adjustable angular momentum vector; (2) an inertial measurement unit (IMU) to detect device tilt and orientation; and (3) a small display that reflects the form factor of a mobile tablet or phone.

GyroTab produces torque on the user's hands that is dependent on the magnitude of the angular momentum when the user rotates the device. This feedback can be used to convey the feeling of weight or inertia. For example, in a gaming application where the user is tilting the device to drive a car, the feedback can simulate the mass and momentum of the car by resisting the user's attempts to make quick or impossible maneuvers. Similarly, the feedback could be used to convey the difference between a working car and one with a flat tire.

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RELATED WORK

A number of haptic feedback devices, such as the Phantom [4] and HapticMaster, provide kinesthetic feedback like GyroTab. However, they require grounding to counterbalance the output force with an equal and opposite reaction force, thus limiting their applicability to mobile devices. There have also been efforts to produce body-grounded kinesthetic feedback devices like the HapticGear [2]; however, these require cumbersome fitting of the device on a user's body.

There has been some past work in ungrounded kinesthetic feedback in order to remove the need for a ground or counterbalance surface in strong force-feedback devices. TorqueBAR, for example, is a two-handed kinesthetic feedback system that uses a mass moving along a linear path to produce feedback effects like changes in center of mass [5]. Lead-Me creates a sensation of being pulled in a certain direction [1]. Both of these systems, unlike GyroTab, generate feedback in only one dimension.

Other types of ungrounded devices have taken advantage of similar properties of gyroscopes in order to produce feedback. Indeed this *gyroscopic feedback* is the same feedback used in large sea liners and spaceships to counteract the forces of the waves and induce precession as opposed to capsizing. Several devices take advantage of these gyroscopic effects, by either actively torqueing a spinning mass quickly [6] to create a push-pull sensation or rotating three disks at different speeds to produce angular momentum changes [8]. These devices, however, generate three-dimensional feedback, which makes them non-flat and hard to incorporate into mobile devices. The device presented in [3] also leverages the gyro effect by dynamically braking fast spinning masses to produce opposing torques, but produces relatively weak impulses on the arm. GyroTab, on the other hand, produces dynamic, strong feedback in a reactive manner, which reduces the mechanical requirements for the device.

In this paper, we describe the design and implementation of GyroTab, summarize the kinds of feedback we can generate with potential applications, discuss some initial psychophysical results we obtained from our user study, and conclude with a discussion on improvements.

THE GYROTAB

GyroTab leverages Newton's first law of physics, which states that objects in motion tend to stay in motion. In a rotational system, this law manifests itself as the *gyro effect*: spinning masses tend to continue spinning, in the same direction, along the same axis. Thus, any torque exerted on a spinning mass will result in the mass exerting a torque back, in a perpendicular direction from the input axis (see Figure 2). The magnitude of these torques is dependent on factors that influence the angular momentum of the device, namely mass, speed of rotation, and radius. Also of importance is the angular speed at which the masses are torqued, which depends on both the velocity and the length of the lever arm.

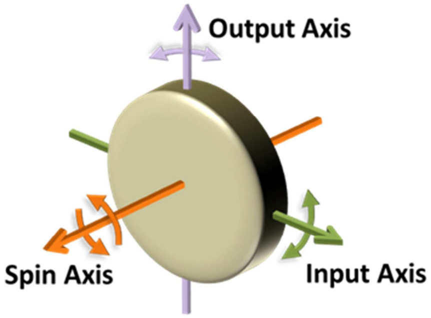

Figure 2: The *gyro effect* illustrated.

Prototype and Implementation Overview

GyroTab consists of a feedback system and a sensing system (Figure 3). The feedback system leverages the gyro effect by spinning two flat, disk-shaped masses along the same axis in opposite directions. When these masses rotate at the same speed, the net angular momentum vector is zero, and the device does not produce any feedback. When one mass is accelerated and/or the other is decelerated, the device produces feedback. In this case, the resultant angular momentum vector will produce an output torque whenever the user rotates the device along an axis other than the spin axis. GyroTab's rotating masses are aligned with the plane of the screen, allowing the prototype to be relatively flat.

Although the same effect could be achieved by accelerating and decelerating a single platter, spinning a mass from rest requires up to several seconds, introducing significant latency. By maintaining two masses in constant motion, GyroTab can vary the supplied feedback quickly by braking one motor and accelerating the other.

In our prototype, the spinning masses themselves are constructed from desktop computer hard drive components (Figure 3). Specifically, we removed the motor-and-platter assembly from several Western Digital WD2500 hard drives, added additional platters to increase mass (and thus increase feedback), and overclocked the motors from 7,200 to 11,000 RPM. The net result is an increase in total angular momentum of about two-fold relative to stock hard drives. In our prototype, the total mass of the platters in each hard drive assembly was 114.7g, and the radius was 4.75cm. Each assembly had a top speed of approximately 11,000 RPM for a maximum angular momentum of 0.0474J-s. Since low weight is of paramount importance to handheld devices, the weight of the system can be reduced without affecting the feedback by increasing the platter's speed.

We chose hard drives because their form factor was conducive to generating large angular momentums (large-radius platters and fast rotations). In addition, hard drive platters are machined and balanced precisely to prevent vibration at high speeds. Hard drives also use high-turn motors, which achieve speeds in excess of 10,000 RPM. We controlled the drive motors with Exceed-RC Proton-18A electronic speed

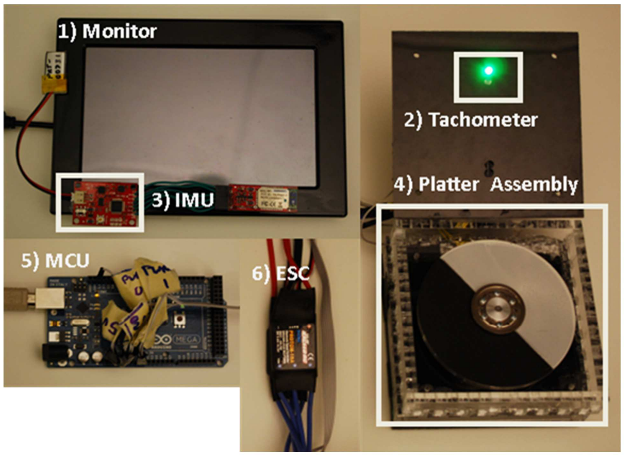

Figure 3: Internal view of GyroTab.

controllers (ESCs). These speed controllers allow us to dynamically vary the speeds of the masses and provide EMF-based braking.

The hard drive platters and drive motors are simply sandwiched together with a short standoff. Multiple platter units could be placed side-by-side to further reduce depth. The feedback system also includes a digital tachometer, which consists of an LED, a photoresistor, and a painted pattern on the hard drive platter to measure the rotational speed of the drives (see Figure 3). We used tachometers in order to provide precise feedback to the ESCs and thus allow consistent control of the motors. The feedback system was controlled using an Atmel ATmega2560 microcontroller connected to the PWM interfaces of the ESCs.

For tilt input, we used a SparkFun Razor 9-DOF inertial measurement unit, which includes an accelerometer, a gyroscope, and a magnetometer. Additionally, we attached a screen on top of the device to simulate the integration of GyroTab's feedback into a mobile form factor.

Although our current prototype is slightly large (currently 4cm thick), the device could conceivably be much smaller if we used custom components rather than hard drive parts. In our device, we reached the limits of speed and responsiveness with our motors. By including custom motors, speeds could easily be increased 3-5 fold without a loss of responsiveness; many commercial RC airplane motors have comparable specifications. By increasing the speed, the device could be made lighter and flatter. Using denser platters could also help reduce GyroTab's width, which would ease integration into a consumer tablet device.

ACHIEVABLE FEEDBACK

GyroTab is capable of achieving varying levels of feedback by varying the relative angular momentum of the spinning masses. In this section, we present the sensations that were presented to participants during our study, and we present anecdotal observations of additional sensations participants described when using GyroTab. This is not a comprehensive list, but provides a sense of how GyroTab may be incorporated into various applications.

Differences in weight

Output torques from the device are generally perceived as *resistance*, making a virtual object harder to move around. We found that increasing the angular momentum of the system could help to convey differences in the weight of a virtual object (for example, a vehicle in a game), with higher angular momentums corresponding to heavier weights. We envision applications in gaming or tilt-controlled user interfaces. This could also be built into handheld measurement equipment that requires restricting the rate at which users can tilt the device.

Path guidance

The torques from the device can also be used to create the feeling that the device is tugging the user's hands along a path. This perception is based on the fact that the output vector is perpendicular to the input vector defined by the user's own torque. We envision this sensation being useful in applications such as real-time remote navigation of a robot or robotic arm that is intended to follow a certain trajectory or avoid obstacles.

Simulated physical media

Varying GyroTab's feedback can simulate motion of a virtual object through different physical media. For example, more feedback (and thus more resistance to motion) corresponds to more viscous media. Similarly, the same mechanism can be used to simulate friction between a moving on-screen object and an on-screen surface. This could, for example, make a virtual ball easier or harder to control as the surface it rolls on changes. Beyond gaming, this could be extended to any tilt-controlled interface to allow the user to detect UI boundaries, for example.

Momentum

Finally, the device can be used to covey the momentum of a moving object. As described above, the feedback could be used to make it difficult to turn a car in a video game, just as the forward momentum of a physical car makes it physically resistant to quick turns. This is perhaps the most intuitive of these proposed effects, because the feedback itself originates from the momentum of physical masses.

STUDYING PERCEIVED FEEDBACK LEVELS

We conducted a small study to explore feedback levels users could perceive with GyroTab. Six participants (three female) aged 25 to 37 performed two tasks, in which we evaluated their ability to perceive *Absolute* and *Relative* levels of haptic feedback.

In the Absolute test, participants were asked to perform a simple gesture: tilting the device forward, back, left, and right, while they were presented with five levels of feedback (i.e., levels of net angular momentum). Participants performed the gesture as many times as necessary to allow them to analyze each level appropriately. They were first shown each of the five levels in order in a tutorial phase, and were then presented with 15 trials (three trials at each of the five levels) in a randomized order. They were asked to label the feedback level from 1 to 5 in each trial, and were required to place the device back on the table after each trial.

In the Relative test, participants were presented with sequences of two different feedback levels (not the same levels used for the Absolute test). During each presentation of a feedback level, participants performed the same gesture described above. After each pair, participants were asked to rate the second feedback level as higher than, lower than, or the same as the first. Participants were presented with six different deltas (the difference between the two levels): 50%, 40%, 30%, 20%, 10%, and 0% of the device's maximum. Participants performed 30 trials: five each of the six deltas. Participants put down the device before the feedback was changed and were fed white noise through headphones to ensure they did not exploit auditory queues.

For the Absolute test results, participants could very reliably (100%) differentiate between the two most extreme levels However, the average accuracy was not as high for precisely identifying a specific level (49%). This may have been because they were required to put the device down after each trial. However, most of the errors were only one-level errors. Thus, when remapping our feedback levels to a coarser resolution, the results are much better. With three absolute levels, the accuracy rises to 95%. Fewer errors occurred at the highest levels, which implies that a larger dynamic range with a bias toward the higher end may improve accuracy.

Results (Figure 4) suggest that participants were very effective in detecting high deltas (~90% accuracy at 50% and 40% deltas) and fairly effective in detecting low and no deltas (~75% accuracy at 30%, 20%, and 0% deltas), but ineffective in measuring very small deltas (~20% accuracy at 10% delta). This implies that users would be able to identify small changes in applications that have continuously changing torque, but also that applications might leverage relative delta changes, rather than encoding feedback using absolute amounts, when many levels are needed.

DISCUSSION AND FUTURE WORK

GyroTab is a device that produces reactive gyroscopic haptic feedback. The key contributions of this paper are: (1) the use of spinning masses to produce reactive gyroscopic feedback; (2) a discussion of the various kinds of feedback that can be generated with this approach; (3) initial results of the perceptibility of the feedback from a user study.

The study presented above provides early evidence that this approach produces several discernible feedback levels, but more work is needed to determine if the resolution accuracy could be improved with a higher dynamic range and different strategies for quantizing the feedback levels.

While conducting this quantitative exploration, we also received positive comments about the haptic feedback itself and the breadth of the perceptual space it suggests; in fact, most of the concepts described in the "Achievable Feedback" section were discovered by our participants. This space becomes even broader when we consider incorporating appropriate audio-visual cues to enhance the feedback.

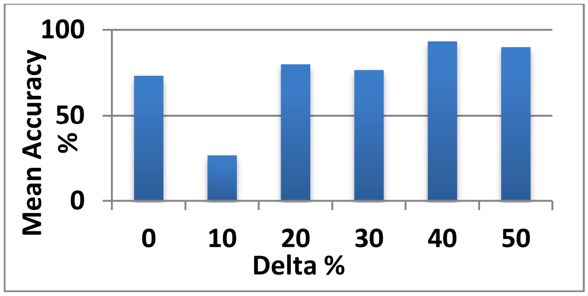

Figure 4: Results for the relative change experiment. Participants were able to discern small relative changes (20%).

The areas of improvement for this device lie primarily in making it truly mobile and increasing the speed at which the feedback can be created (i.e., the rate at which the angular momentum can be changed). In addition, the current device consumes just over 10W while spinning, so power reduction will be essential to integration into mobile devices. Strategically switching between completely off and idle mode could help alleviate some of the power concerns, but custom motors and smaller platters will likely be required.

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