ScratchVR: Low-Cost, Calibration-Free Sensing for Tactile Input on Mobile Virtual Reality Enclosures

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ABSTRACT

We extend the interaction space of low-cost mobile virtual reality (VR) by introducing bidirectional scrolling and discrete selection using magnetic sensing. Our design uses the original Google Cardboard v1 input components, modifying only the cardboard mounted on the side. Users slide the magnetized washer around a circular track on the outer layer, which drags a magnet on the inner layer across asymmetric patterned ridges. The phone's magnetometer detects the position of the magnet as it moves around the track and slots into each ridge, emulating a click wheel. The phone's accelerometer is used to recognize center button taps. We compare our system against the current best practice (gaze) with 12 participants across four VR navigation and selection tasks. Finally, we demonstrate our system robustly handles continuous input, despite some minor deterioration of the cardboard, using a motorized rig over an 8-hour period.

ACM Classification Keywords

H.5.2. [Information Interfaces and Presentation]: User Interfaces — Input Devices and Strategies.

Author Keywords

Mobile; virtual reality (VR); low-cost; magnetic sensing; tactile input; interfaces; machine learning

INTRODUCTION

Low-cost VR enclosures have surfaced as a way to repurpose the mobile phone for an immersive VR experience. Google Cardboard was announced in 2014 and is a fold-out cardboard viewer. These enclosure kits enabled VR to rapidly grow in the commercial and consumer space. However, despite the potential for what mobile VR could enable, once the phone is inside the enclosure, its touchscreen remains unavailable and the enclosure input capabilities are minimal. Despite the advent of more costly standalone mobile VR headsets, there remains a large base of potential users who could benefit from richer input on low-cost VR enclosures.

Figure 1: ScratchVR is a low-cost technique for mobile VR headsets, such as Google Cardboard, to expand the interaction space by introducing bidirectional scrolling using a click wheel design. (a) User interacting with ScratchVR; (b) Spinning washer is used as the human interface; (c) Magnet in the inner cardboard layer slots into place for more reliable recognition and haptic feedback.

Our work seeks to address the gap for input on mobile VR enclosures with magnetic sensing. For VR enclosures to become fully mobile platforms and enable a richer experience, our work demonstrates a low-cost and simple, yet effective, approach to providing calibration-free finger input.

Our work makes the following contributions:

- We describe an approach for tactile finger input with bidirectional navigation and selection using magnetic sensing. Our method is geared towards low-cost mobile VR by repurposing the materials from the Google Cardboard v1.
- We provide empirical evidence of the performance and speed of our system through a within-subjects user study with 12 participants across three modalities (gaze, gaze+tap, scratch) and four navigation/selection use cases (tool palette, app launcher, volume slider, contact list).

RELATED WORK

Researchers have augmented the input capabilities of mobile VR headsets through a variety of ways, including developing new ways to use the sensors in the embedded smartphone. One particular sensing modality researchers have explored, including our present work, is magnetic sensing. Smus and Riederer [3] presented a magnetic input technique to enable

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click selection on the original Google Cardboard v1. The mechanism is wireless, unpowered, inexpensive, and provides physical feedback as the user 'clicks' their finger on the outside of the cardboard by moving a pull and release magnet. The technique also requires no calibration and worked across smartphones, but it only supported single click interactions. We extend this work to provide 3-way input for scrolling and discrete selection of interface elements.

Lyons [1] expanded on the initial magnet-based work developed by Smus et al. [3] by enabling 2D tracking of the magnet on the side of a Google Cardboard enclosure. The work tackled the challenge of dealing with the ambient geomagnetic field, and presented a solution which uses the phone's inertial sensors to account for head movement. While the technique allowed 2D tracing with the finger, the technique required calibration and stronger magnets. Additionally, tracing in 2D requires guided attention and targeting which is useful for drawing, but unnecessary for most targeting and selection tasks in VR. Our technique does not require calibration, and uses a center button area for tap selection and an infinitely long circular track for bidirectional navigation.

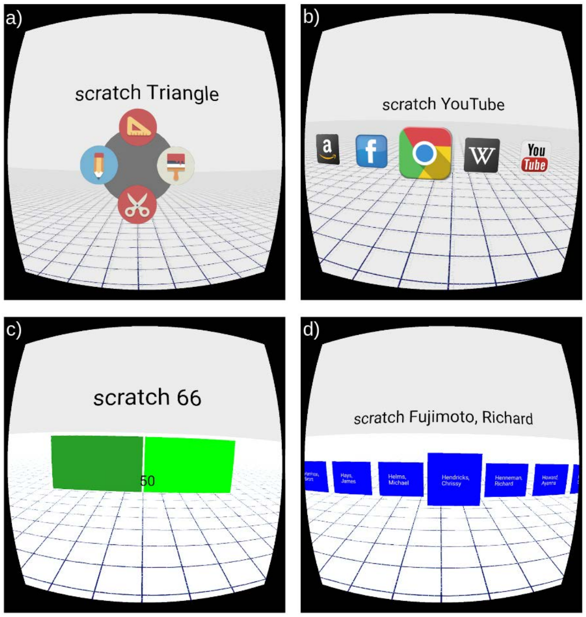

Figure 2: Commonly used menus in VR environments: (a) a pie menu, like a tool palette; (b) a linear menu, like a home screen for launching apps; (c) a volume slider or enumerator, to select continuous range values; (d) a contact list, for selecting a person's name from a long list.

SCRATCHVR IMPLEMENTATION

We modify an off-the-shelf Google Cardboard v1 by attaching the ScratchVR accessory to the headset via velcro. The attachment consists of three components repurposed from the original Google Cardboard: the cardboard frame, a permanent magnet, and a ferromagnetic washer. The cardboard frame is made up of three layers: the top layer is a circular track for the washer to slide along, the middle layer keeps the washer and magnet separated, and the bottom layer is a round track with 10 evenly spaced ridges (Figure 1).

The user operates the apparatus by sliding the washer along the circular track, which in turn drags the magnet along the ridged track in the inner layer. The washer's track is designed to have a larger radius than the magnet's track in order to pull the magnet into the ridges. The result is two-fold: the magnet is encouraged to slot into specific positions, and the user experiences haptic feedback as the magnet slots into position. The magnetic field is strong enough to prevent the washer from falling out under normal operation.

Magnetic and Inertial Sensing

To support bidirectional input, we track the position of the washer/magnet system by training a 10-class support vector machine (SVM) on raw 3-axis magnetometer and accelerometer signals, with each class corresponding to a different slot position of the magnet. The accelerometer signals are included to account for interference from head movement and the Earth's magnetic field. We propose a simple per-device, one-time factory training procedure to enable a calibration-free, out-of-the-box experience for end users. During the training process, the headset is moved around randomly for 1 minute with the magnet in each of one of 10 slots, totaling 10 minutes of data. We validate this procedure by collecting data with an LG G3 Android smartphone, with the sensors set to poll as fast as allowed by the operating system, resulting in a sample rate around 60Hz. Scikit-learn's Support Vector Classification (SVC) implementation is used, and 10-fold cross validation with a 70% split resulted in 99.999% accuracy in determining in which of the 10 slots the magnet resided. A model trained on all 10 minutes of data is used for the study and runs live on the phone.

We also developed a set of handcrafted heuristics based on the accelerometer signal to detect tapping in real-time. The heuristics are based on basic features extracted from a sliding window, including *min*, *max*, *root mean square*, and *deltas* between values. Tap detection is inspired by CardboardSense [4] and is not a core contribution of our work.

INTERACTION EVALUATION

We evaluate three interaction modalities: gaze for navigation and selection (*gaze*), gaze for navigation with tap for selection (*gaze+tap*), and scratch for navigation with tap for selection (*scratch*).

Gaze: We selected the gaze dwell-to-select interaction, a common technique for mobile VR headsets without controllers, as a baseline for comparison. Users hold their view toward the item they wish to select for a specified amount of time. Majaranta et al. [2] indicated their gaze-based experiments with novices used a constant dwell time, typically between 450 and 1000 ms, for selection. We set the dwell time to 750 ms as a fair comparison vs. scratch on task completion times.

Gaze + Tap: We also compared our system with a gaze and tap interaction, in which users place their gaze over the element they wish to select, then tap the center button of our interface to complete the selection. For both gaze-based interaction modalities, we display a visual reticle at all times.

Scratch: Our ScratchVR system provides scrolling and selection interactions. Spinning the washer counterclockwise or clockwise moves the cursor either left/right or up/down, depending on the menu orientation. Selection is performed by tapping the center button.

Interaction Tasks

We develop four common user interface menu elements with unique numbers (i.e., 4, 5, 20, and 100) of selection items. Example applications of these elements were used to evaluate the system in a realistic way:

Tool palette: Circular menu that gives the user access to four common paint operations. Cursor wraps around.

App launcher: Standard linear menu from which users can launch one of five apps. Cursor does not wrap around.

Volume slider: Enumerator that allows users to select continuous range values to set the volume. Cursor moves at increments of 5%, resulting in 20 possible positions.

Contact list: Long scrollable list of contact names that does not fit within the field of view. The user is asked to find a specific person's name in an alphabetized list of 100 people.

For the gaze interaction, scrolling through the contact list is accomplished by looking off-center; the scrolling speed is proportional to how far off-center the reticle is.

Procedure

We recruited 12 participants (6M, 6F, ages 20-25) to take part in our 1-hour laboratory study. All participants were students or researchers, and all but one of the participants had never used VR before. The procedure consisted of:

1. An introductory session to help participants acclimate to using VR. Participants watched a YouTube 360 video of their choice and sat in a swivel chair to encourage them to look around in the virtual environment.
2. A preparation session to introduce each of the menus and interactions. The session consisted of participants completing each condition once, but with only a few (i.e., three) menu items to select each time.
3. The study session to complete navigation/selection tasks across 4 interface elements and 3 modalities, a total of 12 conditions. Study used a partially counterbalanced Latin square with random assignment to determine the order of the conditions per participant. Participants were prompted 12 times per condition, yielding 144 selections per participant.

To ensure a large variance of movements between selections, each of the smaller tasks (i.e., tool palette and app launcher) required each of 1 through $n-1$ moves, where n is the number of elements in the menu. For example, in conditions that use the tool palette (4 items, at most 3 possible jumps), the items to be selected are 1, 2, and 3 items apart. Each of these distances are used 4 times. For the larger tasks (i.e., volume slider and contact list), we divide the total length of the menus into 12 regions. Each task requires users to move through individual elements from 1 to 11 regions away to select a given element within that region.

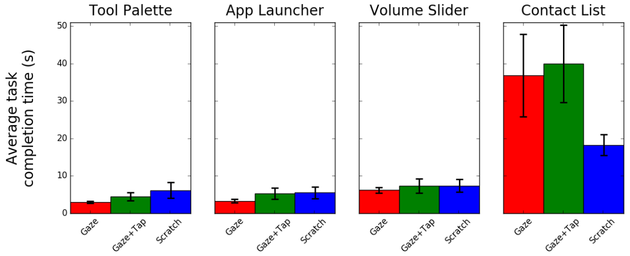

Figure 3: Average task completion time per condition.

RESULTS AND DISCUSSION

User Performance and Feedback

For evaluation, we were primarily concerned with comparing scratch and gaze as interaction modalities. We collected data on task completion times, and participants completed a NASA TLX (Task Load Index) to measure task workload and a survey for open-ended feedback.

Gaze was well suited and effective for smaller menu tasks, while scratch was more suitable for larger menus. By comparing the time taken to complete each task per modality, we observed that the difference between gaze and scratch steadily decreased as the number of menu elements increased (margins of 3.114s, 2.237s, and 1.118s for the 4-, 5-, and 20-item interfaces, respectively), with scratch ultimately taking less than half the time of gaze on the 100-item contact list interface (Figure 3). In a prior pilot study, we discovered the advantage of scratch in larger menus. Thus, we designed the contact list to exhibit this advantage. We believe that larger menus and longer navigation experiences are discouraged in VR due to a lack of suitable existing interaction modalities to support them. Our infinite circular clickwheel system is ideal for large range, continuous input. Furthermore, our findings anecdotally suggest that gaze and scratch could actually serve as complementary techniques, in which scratch could be used for coarse and continuous navigation, while gaze is used for more precise selection.

Overall, scratch was less mentally strenuous than gaze. Since gaze-based approaches utilize head and eye movement for both navigating the environment as well as selecting, they require greater precision on the user's part. This scenario is particularly relevant to users on low-end devices, where lower resolution screens and higher latencies are common. NASA TLX findings supported this claim. Subjects indicated that scratch was both the least mentally demanding ($p < 0.05$) and least frustrating ($p < 0.01$) (Figure 4). As expected, users felt more of a physical demand when using scratch over gaze because of the additional use of a finger. However, this side effect complies with the Google Cardboard design guidelines[1], which advise against including a head strap to encourage users to rest more often and thus reduce the likelihood of "VR sickness."

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[1] `https://vr.google.com/intl/en_ca/cardboard/`

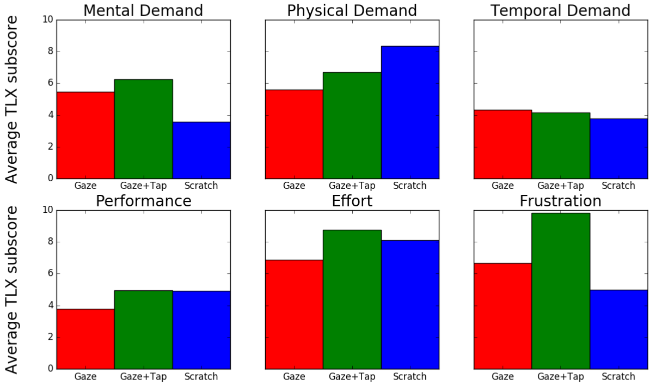

Figure 4: Average NASA TLX scores across input modalities - *gaze* (red), *gaze+tap* (green), and *scratch* (blue). Higher scores indicate greater workload.

Most subjects further illustrated the issue of strain through qualitative feedback, reporting that accidental or incorrect selection when using gaze was a constant concern. On the other hand, users enjoyed scratch because it relieved neck and eye strain from gaze, and "gave you the option to select something without being hyper aware of your positioning."

False Positive Activations

During the acclimation step of the study, while users watched YouTube 360 videos, there was no intentional interaction with our system. In the background, we collected a dataset of over 90 minutes of accelerometer, gyroscope, magnetometer, and microphone data. Running the inertial and magnetic sensing algorithms on this data offline would inform how many false positives might occur during normal operation of the VR headset. We noted the position of the washer at the beginning of each session as ground truth while participants watched their videos. We found that the magnetic tracking algorithm correctly classified the position of the washer 96% of the time out of the 97-minute dataset on a sample-by-sample basis. Upon visual inspection of the results, the inaccuracies occurred for only two participants. The classifier reported invalid, non-adjacent slot transitions which could be mitigated in the future by applying simple filtering logic.

AUTOMATED OFFLINE SYSTEM EVALUATION

Given the cardboard material used in our system, we wanted to validate our design's durability over time. We constructed a platform (Figure 5) to automate offline testing by spinning the washer of the scratch mechanism continuously over extended durations. We ran the rig for 8 hours, including spinning the washer in both directions, incorporating bursts of continuous spinning, as well as pauses between spins. Meanwhile, we collected magnetometer data, as well as the angle of the mechanical arm, measured using an optical encoder mechanism. We calculated the average accuracy for windows of 10 minutes, resulting in a trend that decreased from 97% to above 90% over the 8 hours. Note that this result is after nearly 8 hours of continuous spinning, while most use cases in real usage would involve occasional and sporadic interactions.

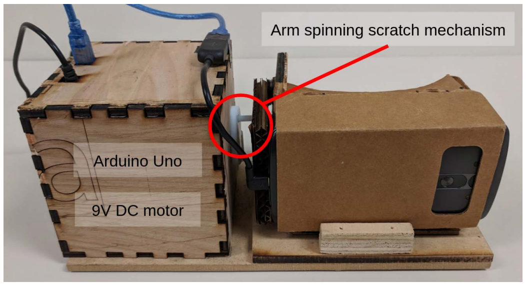

Figure 5: Motorized rig for automated offline testing of *scratch* scrolling interactions.

CONCLUSION

ScratchVR expands the input space for low-cost mobile VR using a modified cardboard enclosure. Our design enables tactile finger interaction on the side of the cardboard enclosure with a 3-way interface for bidirectional scrolling and discrete selection, enabling control of most standard VR interfaces. Our user-independent technique utilizes magnetic sensing and is calibration-free. We provide empirical evidence of the performance and speed of our system through a user study with 12 participants, across three interaction modalities (i.e., gaze, gaze+tap, scratch) and four interaction tasks (i.e., tool palette, app launcher, volume slider, contact list). Furthermore, we present results of the performance of our system over time using a motorized testing rig that continuously simulates bidirectional scrolling. Our cardboard enclosure is able to handle continuous input over an extended 8 hour period, despite some visible deterioration. We embrace the goal of making VR technologies accessible, and seek to provide an input solution that supports a wider breadth of immersive experiences.

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