Improving Inclusion of Virtual Reality Through Enhancing Interactions in Low-Fidelity VR

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ABSTRACT

Virtual reality (VR) is positioned to become a technology for everyday use; we are beginning to see a shift in VR from primarily being for entertainment to supporting office work, socializing, and everyday tasks. Despite falling prices of modern VR devices, their cost remains high, presenting a barrier to VR access for a large portion of the population. This barrier primarily prevents people of lower socio-economic status from accessing a technology and participating in what may soon be a predominant computing paradigm. Low-fi VR, a low-cost alternative, has potential to democratize VR, increase its inclusivity, and diversify research participants in this space. However, its limited interaction capabilities and input options prevents low-fi VR from supporting most productive VR applications or offering effective VR experiences. This position paper explores the current state of low-fi VR hardware and interactions, identifying current problems and potential solutions, and discusses the benefits low-fi VR can provide if advancements are made.

Keywords: Virtual reality, Google Cardboard, mobile VR, EDI.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality

1 BACKGROUND AND MOTIVATION

Virtual reality (VR) and mixed reality (MR) – collectively extended reality (XR) – have seen steadily increasing interest for use beyond entertainment applications (e.g., games). XR systems are now being promoted as everyday technology for work, learning, and socializing. As recently as December 2023, all Meta Quest headsets began supporting Microsoft Office applications. Despite falling costs, and the commodity devices now being less than $1000 USD, they are still prohibitively expensive for large segments of the population. Currently, VR is seen as a luxury and non-essential for everyday life. However, like the smartphone, if VR becomes omnipresent and immersive virtual worlds become the new norm for online interactions and work and learning spaces, the digital divide – the gap between those with access to technology and those without – will widen as people of lower socioeconomic statuses will be unable to participate. Past work proposed the idea of a "virtual reality divide" initiated by the COVID-19 pandemic [14]. They found the pandemic widened the gap between digitally advantaged and disadvantaged households and positively influenced the perceived usefulness of XR and users' intentions to purchase XR hardware.

The latest VR head-mounted displays (HMD) provide head, hand, body, and eye tracking, 106-120° field of view (FOV), and support two 6 degrees of freedom (DOF) controllers. They typically cost between $500-3500 USD, while higher-end models advertised for training and simulation use cost closer to $10,000 USD. This is prohibitively expensive for a large subset of the global population. In contrast, low-fidelity VR headsets ranging in price from $11-55 USD have been available since 2014. Low-fi VR devices are also commonly referred to as mobile VR (MVR), as they use a smartphone inserted into a plastic or cardboard shell as the hardware. However, these systems have significant shortcomings compared to modern VR HMDs, particularly in terms of their interaction capabilities.

Due to lacking dedicated 3D sensing capabilities available on all modern high-end VR devices, MVR cannot support even the most common and simplest VR interaction techniques (i.e., ray-casting or virtual hands using a handheld controller). Since most VR applications require some form of interaction (e.g., for object selection/manipulation, or travel), MVR users cannot truly experience the benefits of immersive VR or participate in a platform that may soon become the norm for work, socializing, and entertainment. A 2023 survey of 298 participants of diverse age, household income, and education, found 70% of people owned VR hardware. However, the majority owned MVR HMDs and only 15% owned high-end VR HMDs [14]. This finding highlights how the majority of VR research, whose focus is on high-end VR experiences, does not benefit a large majority of VR users.

2 POTENTIAL OF LOW-FI VR

While MVR cannot currently compare to modern VR experiences, we argue that improving MVR's interaction, software support, and availability can enhance the inclusivity of VR more generally. VR's userbase could then expand across economic statuses and to more geographic regions. A side-benefit of improving MVR interaction is that MVR HMDs can potentially be used more widely across VR user studies. In this field, user study participants are mainly comprised of the M-WEIRD population (Male, White, Educated, Industrialized, Rich, Democratic) [35] and sourced from universities. Given the hardware is expensive and not always portable, it is often unrealistic or infeasible to conduct VR human participant studies outside of a lab setting. However, the low-cost and ultimately disposable nature of MVR HMDs means they can be ordered and sent directly to participants, reducing geographic limitations for participant recruitment [10, 19] and reaching broader more representative participant populations including people in developing countries [17]. The low price of MVR can also encourage schools, libraries, and other public centers with low funding to provide VR experiences to its students and patrons.

Outside of entertainment, low-fi VR is currently used in education and training [1, 23, 30, 32, 46], health [17, 26, 40, 41, 48], and tourism [27, 42]. Google Cardboard is a popular platform for school use given its affordable price. A systematic review published in 2024 examined 35 studies investigating Google Cardboard use for education [46]. Google Cardboard has also been deployed for clinical practices [26, 41, 48] and psychological and social wellbeing interventions [17, 26, 40]. Since the COVID-

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Figure 1: Low-fi HMDs. Starting from the left: Google Cardboard, Homido Prime, Samsung Gear VR, Google Daydream, and Destek V5.

19 pandemic, a rise in research examining VR virtual tourism was seen, including studies utilizing the Google Cardboard [27, 42].

Unfortunately, there is relatively little recent research on improving the interaction capabilities of low-fi VR. This position paper effectively serves as a call to action to the VR research community, that because of its potential benefits, we should collectively direct more focus on improving low-fi VR hardware, software, and interactions as this affordable technology can improve inclusion of VR access and research.

3 CURRENT STATE OF LOW-FI VR

In the following section, we describe the current state of low-fi VR hardware, supported interactions, and common applications. All HMDs discussed are seen in Figure 1.

The most affordable and widely adopted MVR HMD is the Google Cardboard[1]. The second of two versions, released in 2015, is made of cardboard with an 80° FOV and conductive lever on its righthand side to simulate touchscreen taps. There has been some research on the usability of the Cardboard button [28, 36] and past studies have found its input unreliable [5, 28] and ill-favoured by participants [36]; participants found the button caused arm fatigue, had a poorly designed location, and required two hands to hold the HMD steady while operating. Google Cardboard can support 3DOF head tracking and binary or continuous input using the lever. The low tracking, hardware, and display fidelities greatly limit what interaction techniques, applications, and experiences it can provide [2, 8, 25, 28, 47].

Selection is commonly performed using gaze-directed pointing and dwell time or a lever press as input [5, 12, 25, 47]. Head-gaze is non-ideal as it requires users move the viewpoint to select objects. Cardboard applications tend to have no user-controlled locomotion, but sometimes provide continuous movement that can be stopped and started with binary input control [37].

Most Cardboard applications offer the ability to look around the scene using the smartphone's orientation sensors, and/or provide a passive user experience such as viewing 360° videos [28, 37, 47]. Point-and-shoot games are common [5], but other types of games are not well supported. Along with limited interactivity, the display fidelity of MVR falls short of modern VR HMDs [25, 37] and the processing power of a smartphone cannot handle large, complex experiences without lag or high battery consumption [7]. In general, MVR is made for short experiences with limited to no interaction [13, 28, 37, 47].

Various companies have developed plastic MVR HMDs with superior production quality and more robust hardware that are compatible with Google Cardboard applications. Homido[2], a French company whose goal is to democratize VR, provide a range of HMDs, including the Homido Prime with a 110° FOV and button in the same position as a Google Cardboard. It is sold for $77 USD, but this price may significantly increase as its shipping cost varies regionally (e.g., $87.50 USD shipping cost to Canada).

Some low-fi VR HMDs support a 3DOF tracked Bluetooth controller, but they come with pitfalls. The Samsung Gear VR and Google Daydream HMDs come with a Bluetooth controller capable of 3DOF tracking and raycast interaction. However, the HMDs are only compatible with Samsung or Android smartphones respectively. They were also discontinued in 2017 and 2019 and can now only be purchased through third parties such as Amazon. Their availability and prices are inconsistent, and the technology is no longer supported by their manufacturers. The Destek V5[3], released in 2022, provides a 110° FOV experience with a Bluetooth controller connected to an Android device for input and retails for $34.99-39.99 USD. However, the controller is not tracked and can only be used like a console gaming controller (i.e., controlling movement with a joystick). It is only available in the US or other limited regions through Amazon. While the Destek V5 shows promising improvements in display fidelity, it falls short of public expectations for VR interaction.

In general, low-fi VR HMDs primarily deploy gazed-based interaction with button input. Object selection and UI interactions are commonly supported, but locomotion and object manipulation are scarcely seen across MVR applications. Regardless of HMD model, the smartphone used generally has a lower resolution [25], processing power, and lack of cooling hardware compared to modern VR systems [37]. These hardware limitations prevent MVR from supporting complex applications. Current low-fi HMDs have comparable FOVs to modern HMDs, but their interaction methods are demonstrably worse. At this time, 6DOF head, hand, and controller tracking are not supported, leaving MVR unable to support the majority of VR applications and interaction techniques.

4 IMPROVING LOW-FI VR INTERACTION

The following sections summarize past research on improving fundamental interactions in low-fi VR. Across literature, the following fundamental VR interaction tasks have been identified: object selection and manipulation (acquiring targets, and modifying their properties such as position, orientation, etc.), navigation, which consists of travel (controlling direction and speed of viewpoint movement) and wayfinding (path planning prior to and during travel), system control (issuing commands to system using UI elements), and symbolic input (text entry) [4, 21, 24, 28, 39, 43]. These tasks typically support and act as the building blocks for more complex tasks [21, 24]. While interaction techniques for fundamental and complex tasks have been thoroughly explored and evaluated using modern VR systems, designing effective interactions for low-fi VR remains a sizable issue. After all, the vast majority of complex interaction

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[1] https://arvr.google.com/cardboard/

[2] https://homido.com/en/home/

[3] https://destek.us/collections/smartphone-vr-headset

techniques rely on 6DOF tracking provided by high-fidelity devices [28]. Most past literature focuses on refining these fundamental tasks in low-fi VR.

4.1 Selection, Manipulation, and System Control

Past literature on selection and manipulation in low-fi VR primarily aimed to address four main challenges:

- Selection indication is limited to a single button or dwell time. [8, 11–13, 15, 18, 20, 22, 25, 31, 45, 47]
- Lack of tracking support beyond 3DOF head rotation. [7, 9, 11, 13, 15, 18, 20, 28, 31, 34]
- Insufficient processing power of the smartphone. [7, 9]
- A limited field of view that hinders interaction. [11, 15, 31]

Past research can be categorized by either requiring additional costs (exceeding the price range of a Google Cardboard) or being low cost to maintain low-fi VR's inclusivity. We discuss these three fundamental tasks together as there is heavy overlap between interaction techniques for performing them and they tend to be grouped together in research. We do not discuss symbolic input in low-fi VR as it is still an ongoing challenge in VR research [16]; we instead focus on the design of interactions that can be considered intuitive in VR (i.e., grasping objects in 3D) but pose a challenge for MVR given its low fidelity hardware.

4.1.1 Additional-Cost Solutions

Many proposed interaction techniques require external expensive hardware to employ. Requiring extra hardware for proper interaction contradicts the main purpose of low-fi VR as it makes the technology less portable and accessible to users of all socioeconomic statuses [37].

Past solutions have used a smartwatch to support fixed-origin ray-based selection [13, 18]. The watch's inertial sensors provide 3DOF rotational input to direct a ray originating from the centre of the HMD. Selection indication was performed either using the watch face as a button [13] or forearm rotations to mitigate the so-called Heisenberg effect [18] (unintentional movement at the instant of selection resulting in missing the target). Overall, the smartwatch-based techniques facilitated object selection, but did not support 6DOF interactions commonly used in modern VR.

Other previous work focused on using a second smartphone as a 6DOF handheld controller [20, 31]. Mohr et al. [31] determined the pose of a handheld smartphone in the virtual environment (VE) by calculating its relative position to the HMD by using the smartphone camera to track an image marker attached to the front of the HMD. This design can support the virtual hand technique, selection by pointing, object manipulation, and 2D input via the smartphone's screen. Meanwhile, Kyian et al. [20] used a fiducial marker displayed on the smartphone screen and the phone's gyroscope data to determine its position in space. They also displayed the smartphone screen's content on the virtual phone and captured touchscreen data to make the phone usable in VR. Their solution can support common VR selection techniques (i.e., ray, and virtual hand). Of all literature we reviewed, these solutions offered the highest fidelity interaction but largest expense due to the need for a smartphone for an input device.

Other research developed ways to integrate hand tracking into MVR [15, 34]. Park et al. [34] used a Leap Motion[4] sensor attached to the wrist to support in-air gestures for selection and manipulation. While the Leap Motion is more affordable than a smartwatch or smartphone, the computational complexity of this technique was not evaluated, which is a significant consideration when deploying to smartphone-based VR. Meanwhile, Castro et al. [7] used a PC as a server to process hand-pose data extracted from images sent from the smartphone. The result is 6DOF virtual hand interaction; users can perform pinch gestures to select and manipulate objects.

Lastly, past work has yielded external attachments for the HMD to improve system control. Multiple researchers have used a touch screen attached to the front of the HMD with a 1-1 mapping to the FOV to support UI element selection [12, 22]. Similarly, Tseng et al. [45] designed a configurable grid of buttons attached to the front of the HMD [45]. Made for UI interaction, an open palm hand gesture initiates a mechanical extender that dynamically moves the panel of buttons to the same location as the UI buttons in the VE for direct manipulation of UI elements. A tracked glove or depth camera is needed for this technique and the supported interaction is limited to UI selection and manipulation.

Although the aforementioned techniques improve interaction on MVR, the additional cost to do so remains problematic.

4.1.2 Low-Cost Solutions

On the other hand, other work we reviewed ensured their proposed interaction techniques required little to no extra cost to maintain MVR's affordability. Similar to the additional-cost approaches, we found the low-cost techniques either focused on improving tracking in MVR [9, 11, 15, 28] or utilized the HMD surfaces for interaction [8, 25, 47].

Two previous projects investigated optical hand tracking for hand interaction [15, 28]. Using the smartphone camera, Luo et al. [28] tracked the user's hand and fingers to support the virtual hand technique and fixed origin ray-casting by controlling the ray direction with a tracked finger. They tested selection indication using a tap gesture and the Cardboard button but neither performed well. Meanwhile, Huesser et al. [15] used a machine learning system and webcam placed in the user's physical environment to support hand and body gesture tracking. While their solution provides a novel selection indication method, it does not provide 6 or 3DOF hand interaction like previous work.

Similar to Kyian's work [20], our previous work [11] designed a 6DOF optically tracked input device, the Low-Fi VR Controller. Our approach required no additional cost as it is made of cardboard. We formally evaluated the controller for ray-based selection and found it yielded similar selection performance to a modern VR controller if selections are confirmed via dwell time. We evaluated a novel manual selection confirmation but it yielded selection times significantly slower than using the controller with dwell confirmation.

Our survey of literature found one publication that proposed an eye tracking method for selection in low-fi VR [9]. The method used the smartphone's front camera to capture iris images and a pipeline of custom algorithms to track the user's pupils. This method requires no additional hardware or heavy computational processing. It offered comparable accuracy to eye tracking built into modern VR HMDs in the central FOV of ~20°of visual angle. When compared to head-gaze selection, the eye tracker performed as fast and avoided cumbersome head motions.

For Google Cardboard specifically, researchers have used the cardboard surfaces for UI interaction [8, 25, 47]. Two previous projects used machine learning algorithms that detect several tap and sliding surface gestures [8, 47], providing system control interaction and input method. For scrolling menu interaction, a cardboard attachment named ScratchVR was proposed; it is a magnet and washer that can be pushed around a circular track for forward and backward scrolling [25].

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[4] https://www.ultraleap.com/leap-motion-controller-whats-included/

4.2 Travel

Travel, or locomotion, is the most common task in VR [6, 21] and is essential for many applications (e.g., physical rehabilitation) [36]. In MVR applications, users can look around the environment but can seldom actively explore it [36]. Common travel techniques supported on MVR include continuous movement (movement is automated and user controls direction with gaze), travel via the Cardboard button (continuous movement with ability to start and stop by toggling button), and using a Bluetooth controller's touchpad to move in two axes [36]. These techniques have been formally compared, and the results showed continuous movement was the most difficult to operate while the controller was the most favoured by users. Nonetheless, all three techniques have been found ineffective for MVR travel [36].

This dismal state of MVR travel has motivated past research. Menzner et al. [29] designed a travel technique for navigating 2D information spaces in MVR. Using the touch surface of a second smartphone, the user can zoom in and out of a 2D space (i.e., a map) using the relative position of their finger to the touchscreen. This technique was formally evaluated in a target search and acquisition task and it outperformed the pinch-to-zoom and drag-to-pan gestures commonly used with smartphones.

Meanwhile, Papaefthymiou et al. [33] used a second handheld smartphone as a pedometer to support 3DOF real walking. The movement direction is determined by the rotation vector of the handheld smartphone. Similarly, Tregillus [44] developed a walk-in-place (WIP) technique named VR-STEP by using the smartphone inside the Google Cardboard as a pedometer. The walking direction is controlled by user's head tilt; the user can tilt their head in a direction to turn while keeping their gaze directed forward. Given the phone is attached to the head and not in a hand or pocket, VR-STEP requires users to put a 'bounce' in their step, which may feel unnatural. The authors compared VR-STEP to a tilt-only technique (users do not walk but lean their body forward and use head tilts to control direction) and found TiltOnly provided significantly faster travel with fewer collisions.

Ang et al. [3] developed a swing-in-place (SIP) travel technique. It is an extension of VR-STEP that requires a single smartphone and decouples the user's gaze from movement direction. To operate SIP, the user slightly lifts one leg to lean to the opposite side. Acceleration is generated once the user leans and the leaning direction determines their movement direction. The accelerometer and gyroscope of the phone are used. If a user looks to either side causing the phone's orientation to change, this change is accounted for and users' true forward direction is computed meaning user's gaze direction will not affect their travel direction. Overall, SIP was found as immersive and less fatiguing than VR-STEP, and 85% of participants enjoyed the freedom of turning their head while walking as it mimics real life walking.

5 DIRECTIONS FOR FUTURE WORK

Based on our review of current literature on MVR interaction, we have identified potential directions for future work with the goal of improving MVR interaction and application support.

After reviewing proposed selection and manipulation techniques, we identified three major gaps in research. First, there is a need for low-cost techniques that provide effective 6DOF selection and manipulation. Past solutions that effectively support 3 or 6DOF ray-based selection require additional expensive hardware [13, 18, 31], defeating the purpose and diminishing the advantages of low-fi VR. Meanwhile, low-cost solutions primarily supported only system control operations such as UI and menu interactions [8, 25, 45, 47]. The Low-Fi VR controller [11] is a low-cost method for 6DOF ray-casting; however, its selection performance was only comparable to high-end controllers when using dwell activation, which is non-ideal. Its tracking fidelity could also be refined to improve user experience and it has not yet been evaluated for manipulation tasks.

The proposed virtual hand techniques all use a form of hand tracking and supplied 6DOF interaction [7, 28]. While this is an encouraging step towards complex selection and manipulation in MVR, ray-casting is the more common selection technique in VR [4]. In general, future work should investigate low-cost 6DOF selection and manipulation techniques with focus on ray-casting to improve MVR's application support.

The second major gap is the need for a quick and reliable "click" method that can be used universally across MVR applications for selection indication or input in general. As stated in section 3, the Cardboard button has extensive usability issues and selection using dwell time is not ideal. While past work developed effective cardboard-surface tap gestures, using such a method would limit interaction to one hand and potentially cause arm fatigue over time. A manual selection technique using tracked markers was proposed in our previous work [11], but it was found too slow for real-world use. Overall, the design of a reliable input method that is compatible with most or all MVR HMDs and interaction techniques should be explored.

Third, future work should investigate low-cost methods for increasing camera-tracking boundaries to support interactions outside the central FOV of the camera. A consistent issue across literature is the small FOV of the camera impeding tracking and interaction fidelity [9, 11, 28, 34]. Hence, future work should explore ways to artificially increase the tracking area. Mohr et al. [31] did just this, but their solution requires a second smartphone.

Lastly, after reviewing past research on travel in MVR, we found a lack of research on travel techniques outside of WIP and real walking. Teleportation is commonly employed on commercial VR devices as it allows users to explore large virtual environments and helps prevent cybersickness [38]. It is rarely seen in MVR but has the potential to significantly improve its variety of supported applications. A major limitation of current MVR applications is a lack of active exploration [36] despite navigation being a core task of VR [21]. Future work should explore the design of interaction techniques that support active exploration, as this can greatly increase the kinds of applications MVR can support and thus bring the low-fi VR experience closer to modern VR.

6 CONCLUSION

VR is positioned to become a primary platform for work, learning, socializing, and everyday tasks, but its high-cost barrier to access marginalizes a large portion of the population. Low-fi VR has potential to democratize VR access and diversify VR study participant pools, but its lack of input and interaction methods inhibits it from supporting productive VR applications and fundamental interaction techniques. The poor state of low-fi VR interaction precludes people of lower socioeconomic status from effectively participating in what may become a prevalent computing paradigm [2, 8, 11, 25, 28, 47, 49]. Motivated by this problem, we investigated the current state of low-fi VR interaction research to identify underexplored research opportunities for improving fundamental interactions in low-fi VR. This position paper poses a challenge to the VR research community to explore ways of advancing low-fi VR hardware, software, and interactions as this technology is imperative to improve the inclusion of VR access and research, but potential solutions are non-obvious.

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