Ball20: An In-Hand Near-Spherical 20-Sided Tangible Controller for Diverse Gesture Interaction in AR/VR

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Abstract

Spherical tangible devices have been explored to support effective object manipulation and enhance immersive experiences in augmented and virtual reality environments. However, because their spherical form makes it difficult to incorporate traditional input channels, their applicability and use as general-purpose input devices remain limited. In this paper, we present the Ball20, an in-hand near-spherical 20-sided tangible controller with independent force sensing on each face, designed to enable diverse gesture interactions. We developed the Ball20 hardware, designed a gesture set, and implemented a drawing application to demonstrate the Ball20 concept. In the first user study, we evaluated the feasibility of using the Ball20 for a drawing application and collected feedback. In the second user study, we further refined the Ball20 and conducted a quantitative usability evaluation.

CCS Concepts

• **Human-centered computing → Interaction devices**; **Virtual reality**.

Keywords

Ball20, Spherical Tangible Device, VR, AR

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1 Introduction

Tangible User Interfaces (TUIs), particularly those using spherical tangible devices, have been widely studied for their potential to enable more effective and immersive 3D interactions [2, 3, 5, 7, 8, 12, 15]. By allowing users to roll a physical sphere, these interfaces can offer a more direct and embodied approach to manipulating digital content, enhancing the sense of engagement.

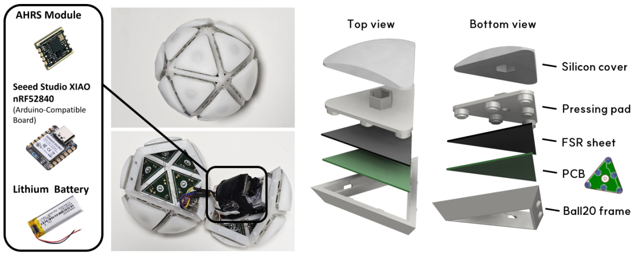
However, effectively integrating traditional input mechanisms, such as physical buttons, into a spherical form factor continues to be a significant challenge. This limitation hinders spherical tangible devices from supporting more complex tasks, restricting their broader use as general-purpose controllers. Previous studies have explored ring-shaped buttons [11], tapping-based inputs [8, 10], pressure-sensitive menus [6], and non-dominant-hand gestures [12]. Although these methods expand input possibilities, they still provide only basic input capabilities.

To address these challenges, we propose Ball20, an in-hand near-spherical tangible controller with 20 independently force-sensing faces. This design enables diverse gesture interactions while maintaining the easy-to-roll characteristics of a spherical device. We present the design and implementation of Ball20, including its hardware and gesture set. We also demonstrate a drawing application that utilizes Ball20's diverse input capabilities. To evaluate the effectiveness of Ball20, we conducted two user studies. In a first user study, we evaluated the feasibility of using Ball20 in a drawing application and gathered feedback. In a second user study, we refined Ball20 further and conducted a quantitative usability evaluation.

2 Related Works

2.1 Spherical Tangible Devices for Various Input

Efforts to extend spherical tangible devices beyond simple manipulation have been explored in previous studies. Some studies introduced ring-shaped buttons [11] or tapping-based inputs [8], and others relied on dwell-based methods [2] to enable additional input. However, these approaches provided a limited range of additional interaction. To support more diverse inputs, Louis et al. [10] developed Handheld Perspective-Corrected Displays (HPCDs), allowing general-purpose interaction through touch sensing and



(a) The appearance and internal structure of Ball20. (b) The single-face structure of Ball20.

Figure 1: The appearance and structure of Ball20: (a) The appearance and internal structure of Ball20. (b) The single-face structure of Ball20.

6-DOF movements. They implemented widgets and radial hierarchical menus for command selection, but their system required multiple steps for each command, limiting interaction speed and efficiency. Similarly, Satriadi et al. [13] proposed a tangible glove that used gestures from the non-dominant hand to enable various interactions, such as touching or swiping the glove, or performing pinch and tap gestures on augmented elements. Although this approach offered diverse functionalities, it constrained bimanual usability, making the device less practical. Other studies have explored adding pressure-sensing capabilities to spherical devices, enabling 3D object manipulation or pressure-based linear menu selection [6, 7]. While these methods broadened interaction possibilities, their potential for more complex tasks or use as general-purpose input techniques remains underexplored.

3 Ball20 Implementation

3.1 Hardware Construction

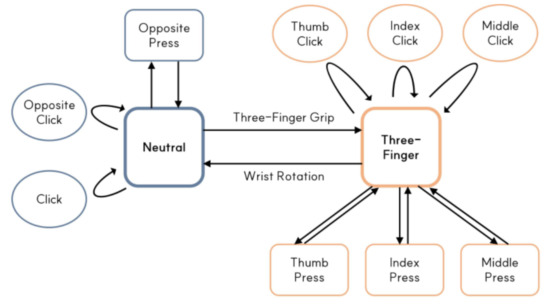
Figure 1(a) shows the overall appearance of the Ball20, a 20-sided device with a near-spherical outer surface. It has a diameter of 75 mm and weighs 92 g. The Ball20 includes an AHRS module (EBIMU-9DOFV5-R3) for orientation tracking and an Arduino-compatible board (Seeed Studio XIAO nRF52840) for data processing. The board collects pressure data from each face and orientation data from the AHRS, then transmits them via Bluetooth. The AHRS communicates with the board via serial communication.

Figure 1(b) illustrates the structure of each face. Each face functions as an individual FSR module. The PCB has six zigzag-shaped exposed traces that serve as a pressing point. On top of the PCB, an FSR sheet (Sensitronics XactFSR) is covered by a pressing pad aligned with the exposed traces. When a surface is pressed, the FSR sheet is also pressed, and its resistance decreases as the applied force increases. Each FSR module is amplified by an operational amplifier (LMV321), and groups of four modules transmit their signals to an ADS7138 ADC, which forwards the data to the Arduino. The silicone cover has a Shore A hardness of 12. The pressing pad and the Ball20 frame were 3D-printed using Formlabs Clear Resin and PLA filament, respectively.

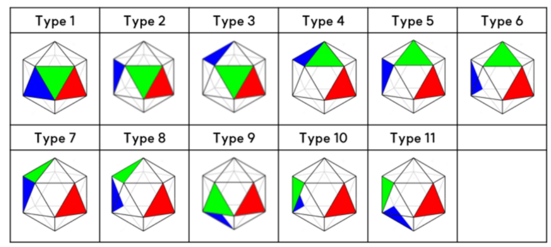
3.2 Gesture Design

We designed a gesture set to enable a variety of gestures using Ball20. Figure 2(a) shows our gesture state machine for Ball20. The gesture set is divided into two modes: Neutral mode and Three-Finger mode. Neutral mode is designed to support the tangible controller's rolling functionality, allowing the user to freely roll the controller and quickly perform gestures such as Click, Opposite Click, and Opposite Press. A Click is performed by quickly grasping Ball20 with the entire hand and then releasing it, while Opposite Click and Opposite Press are performed by pressing two opposite faces simultaneously. Three-Finger mode supports various gestures similar to those of VR controllers, with each face functioning as a button mapped to a specific finger. This mode allows for a broader range of gestures and can detect both Click and Press gestures for each finger. The user can switch to this mode using the "Three-Finger Grip," and can return to Neutral mode by rotating their wrist.

Although we would prefer a more seamless gesture set without distinct modes, allowing the controller to be rolled freely while immediately performing an index click, our current design separates the modes to ensure accurate gesture recognition.



(a) The gesture state machine for Ball20.



(b) The types of grips recognized as Three-Finger grips.

Figure 2: (a) The gesture set is divided into two modes: Neutral mode, which highlights its rollable functionality, and Three-Finger mode, which supports a variety of gestures. (b) The types of grips recognized as Three-Finger grips. The red, green, and blue faces represent the thumb, index, and middle fingers, respectively.

3.3 Gesture Recognition

This section details our gesture recognition method. For calibration, the gain of each sensor was adjusted so that applying 10 N of force to a face corresponds to a sensor reading of 1000. Although the sensor values are not perfectly linear from 0 to 1000 within the 0–10 N range, we assume a linear relationship for simplicity. For example, 1.5 N corresponds to a sensor value of 150.

In Neutral mode, opposite gestures are recognized only if exactly two opposing faces detect finger contact, while the other 18 faces do not. A force of 1.4 N or higher indicates finger contact, whereas anything below 1.4 N is treated as no contact. If the force on the two opposing faces rises quickly and then drops, the system recognizes an Opposite Click. If the total force on those faces exceeds 6 N for at least 0.5 seconds, an Opposite Press is recognized. If neither condition is met, the system checks for a Click. A Click occurs when at least three faces detect contact and the total force rises and then falls, peaking at 8 N or above.

In Three-Finger mode, gestures are recognized for each finger. A Press is detected if the finger force reaches 4 N or more for 0.5 seconds, while a Click occurs if the force increases quickly and then decreases. When executing a finger gesture, unintended force from other fingers can lead to misrecognition, such as a Thumb Click being triggered during an Index Click. To address this, we took into account the pressing force of each hand and applied multipliers of 1.3 and 1.4 to the Index and Middle fingers, respectively. If multiple finger gestures are recognized simultaneously, the system selects the one with the highest force.

To switch from Neutral mode to Three-Finger mode, the "Three-Finger Grip" gesture is used. We define this grip as placing the thumb, index, and middle fingers on distinct faces of the Ball20, holding it in the palm in a manner similar to typical VR controllers, while the ring and pinky fingers support the ball from below. Through heuristic exploration, we identified 11 variations of this Three-Finger Grip that stably hold the Ball20. We classified each variation not only by the faces contacted directly by the thumb, index, and middle fingers, but also by the surfaces (e.g., on the palm side) that necessarily make contact and those outward-facing surfaces that remain non-contact. Based on these contact and non-contact conditions, each grip type was systematically recognized. Figure 2(b) shows the 11 grip types. Although our current Three-Finger Grip recognition is not fully robust, it sufficiently demonstrates the potential of Ball20.

4 Drawing Application using Ball20

We implemented a drawing application to evaluate the usability of the Ball20 concept. It includes basic drawing features and is designed to be used with Ball20's gestures. Figure 3 shows the implemented features and the gestures mapped to them.

Grabbing and Releasing an Object. In Neutral mode, users can touch an object with the hand cursor and perform the Click gesture to grab or release it. In Three-Finger mode, this is done using the Index Click gesture.

Creating a Sphere and Brushing. These actions are mapped to the index finger in Three-Finger mode. The Index Click gesture creates a sphere, while the Index Press gesture, combined with hand movement, enables brush drawing.

Scaling. This feature is available only in Neutral mode. By maintaining the Opposite Press gesture, users enter scaling mode, during which they can adjust an object's size by rotating their wrist.

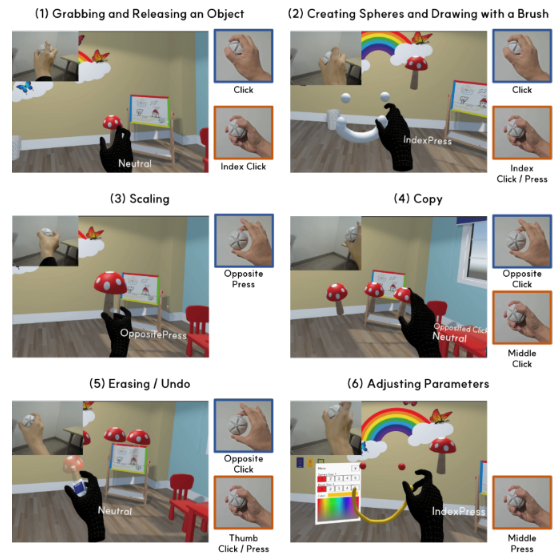


Figure 3: The implemented features in the drawing application and their mapped gestures. Gestures with blue borders represent those in Neutral mode, while gestures with orange borders represent those in Three-Finger mode. The same gesture may perform different functions depending on whether the hand cursor is touching an object.

Copy. In Neutral mode, the Opposite Click gesture copies the object, while in Three-Finger mode, this is done using the Middle Click gesture.

Erasing and Undo. In Neutral mode, users can activate eraser mode by performing the Opposite Click gesture when no object is touched. In Three-Finger mode, the Thumb Press gesture activates eraser mode, and objects can be erased with the Click gesture. Undo is available in Three-Finger mode using the Thumb Click gesture, which deletes the most recently created object.

Adjusting Parameters. The Middle Press gesture triggers a menu plane where parameters such as sphere size, brush thickness, and color can be modified. Users can adjust these settings by pointing at the menu and performing the Click gesture.

5 User Study 1: Exploring the Usability of Ball20 in Drawing Application

We conducted a user study to evaluate the usability of Ball20, specifically whether participants could perform a drawing task using various gestures, and to gather their feedback.

5.1 Participants & Experimental Setup

We recruited 10 participants (M = 24.9, SD = 4.28; 5 females and 5 males) from the university's online community. All participants had used VR devices at least five times. We used a Meta Quest 3 for the VR setup.

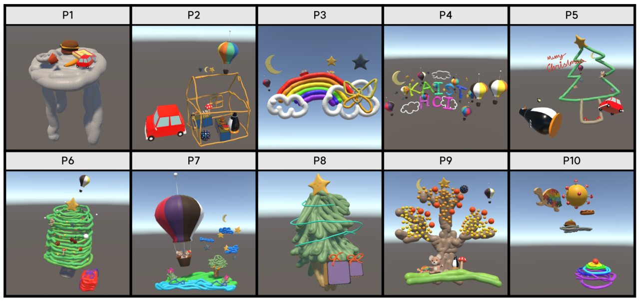


Figure 4: The participants' drawings from the free drawing session in the user study 1.

5.2 Procedure

The experiment consisted of the following steps:

5.2.1 Gesture Training (10 min). Participants learned the gesture set of the Ball20. They first practiced the gestures without wearing the HMD, directly observing the Ball20 and their hands, and then repeated the practice while wearing the HMD.

5.2.2 Drawing Scenario Training (20 min). Participants learned the features and gestures of the drawing application and then practiced freely to familiarize themselves with the drawing application.

5.2.3 Free Drawing (15 min). Participants engaged in a 15-minute free drawing session while standing. They could manipulate various objects to create their drawings. To encourage motivation, they were told that all drawings would be voted on, and that the best drawing would receive a gift card.

5.2.4 Interview (10 min). After the free drawing session, participants reported their experiences with the Ball20 controller.

5.3 Results & Discussion

Figure 4 shows the drawings created by participants during the drawing task session. All participants successfully used the various functions of the Ball20 controller to complete their drawings. Participants generally appreciated the controller's material and grip, noting that the smooth rolling action enabled natural and intuitive interactions. The gesture set was also largely intuitive, especially the actions of using the index finger to draw and the thumb to undo, which were easy to remember and implement. Compared to traditional VR controllers, the Ball20 offered advantages in tasks like rotation and drawing, providing more natural interactions.

Despite these strengths, several limitations were identified. One major issue was the lack of tactile feedback when pressing the surfaces, which caused uncertainty in input recognition and led to finger fatigue from excessive force. Incorporating haptic feedback or tactile cues could enhance input confirmation and reduce strain, thereby improving the device's overall usability. In addition, participants mentioned that they struggled to fully familiarize themselves with the gesture-function mapping within the study time. Simplifying the gesture set and ensuring consistent mappings across modes could address this issue and improve intuitiveness.

(a) Internal structure of Ball20 (b) Brush icon (c) Gesture guide

Figure 5: Improvements in Ball20: (a) an LRA for haptic feedback, (b) a brush icon that replaces the hand cursor while drawing, and (c) gesture mapping guidance based on the current interaction context.

6 User Study 2: Evaluating the Quantitative Usability of Ball20

In the previous user study, participants successfully used Ball20's gestures in a drawing application and provided various feedback. Building on this feedback, we integrate several improvements into Ball20, as illustrated in Figure 5. Specifically, we added haptic feedback with distinct patterns for each gesture, introduced a brush icon to replace the hand cursor during brushing to enhance immersion, and displayed a gesture guide on the user's hand to help recall gesture mappings. In this second user study, we quantitatively evaluate the usability of the improved Ball20 controller.

6.1 Participants & Experimental Setup

We originally recruited 12 participants; however, 2 were unable to participate in the experiment because the gesture recognition (Three-Finger Grip) did not work properly for them, leaving a total of 10 participants (M = 26.7, SD = 4.57; 10 males). All participants had used VR devices at least five times. We used a Meta Quest 3 for the VR setup.

6.2 Procedure

The Gesture Training and Drawing Scenario Training sessions were conducted in the same way as in the first user study. Afterward, participants performed a Drawing Task to replicate a given sample and then completed a survey and interview.

6.2.1 Drawing Task. Participants were asked to replicate a given sample. This sample was designed so that all of Ball20's gestures and functions would be used at least once, allowing for a comprehensive evaluation of its usability. Figure 6 shows the sample model.

6.2.2 Survey & Interview. To gain comprehensive insights into usability, we used three questionnaires. The System Usability Scale (SUS) [1] provided an overall measure of usability. The User Experience Questionnaire (UEQ) [9] assessed classical usability and experiential aspects, such as efficiency, attractiveness, and novelty. Lastly, the NASA-TLX [4] evaluated perceived workload.

6.3 Results

Figure 6 shows the drawings created by participants during the drawing task session. All participants successfully utilized the various functions of the Ball20 controller to complete their drawings.

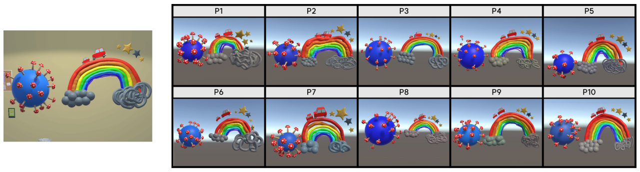


Figure 6: (left) Sample model in the user study 2. (right) The participants' drawings from the drawing task session.

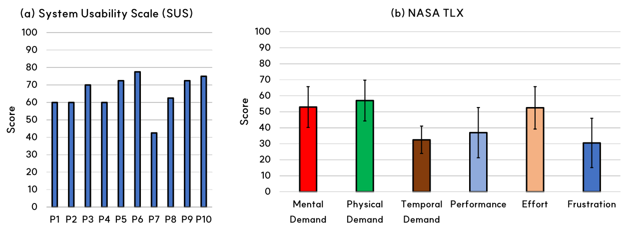


Figure 7: SUS and NASA-TLX Results from the user study. Error bars indicate 95% confidence intervals.

Participants took an average of 676.5 seconds (SD = 70.14) to complete the task.

6.3.1 System Usability Scale. Figure 7(a) shows the SUS scores for each participant. The average score across all participants was 65.25 (SD = 10.43), which is slightly lower than 68, which is the center of the curved grading scale (CGS) used by Sauro and Lewis [14]. This result suggests the need for further improvements to enhance usability.

6.3.2 NASA-TLX. Figure 7(b) shows the NASA-TLX ratings. Participants reported Physical Demand as the highest contributor to overall workload, followed by Mental Demand and Effort. Conversely, Performance, Temporal Demand, and Frustration were rated relatively lower.

6.3.3 User Experience Questionnaire. Figure 8 shows the UEQ score with benchmarks. The UEQ provides benchmark data from a large dataset, where the categories are defined as follows: *Excellent* represents the top 10%, *Good* the top 25%, *Above Average* the top 50%, *Below Average* the top 75%, and *Bad* the top 100%.

For Ball20, the Attractiveness scale—reflecting the overall user experience—scored *Good*. In the hedonic quality scales (Stimulation and Novelty), it achieved *Excellent* scores. For the pragmatic quality scales, Perspicuity scored *Below Average*, while Efficiency and Dependability were *Above Average* and *Good*, respectively.

6.4 Summary & Discussion

Overall, this second user study demonstrated both the benefits and the remaining challenges of the improved Ball20 controller. Integrating haptic feedback—identified as a major need in the previous study—made it easier for participants to recognize gestures. They appreciated the sustained vibration feedback for press states and the distinct click sensation for gesture inputs, although a few mentioned that the vibration was slightly weak and did not fully replicate the feel of a physical button click. Visualizing the brush icon enhanced immersion, making drawing feel more natural. Additionally, the gesture guide reduced confusion about gesture-function mappings, though some participants suggested that using icons could make it more visible.

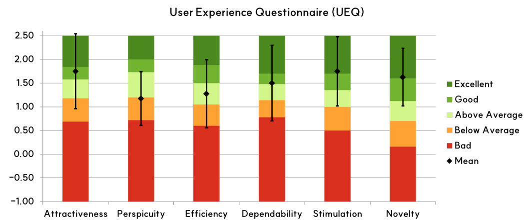


Figure 8: UEQ Results from the user study. Error bars indicate 95% confidence intervals.

The SUS score of 65.25, slightly below the midpoint of 68 on the curved grading scale (CGS) used by Sauro and Lewis [14], indicates that further improvements are needed to enhance usability. While the UEQ rated Stimulation and Novelty as *Excellent*, reflecting strong hedonic qualities, Perspicuity was *Below Average*, aligning with the SUS score and highlighting the need for a clearer, more intuitive gesture interaction. Additionally, the NASA-TLX results showed high Physical and Mental Demand, largely due to the difficulty of switching between Neutral and Three-Finger modes, which increased strain and cognitive effort.

7 Conclusion

In this paper, we proposed Ball20, an in-hand near-spherical tangible controller with 20 independently force-sensing faces. Through drawing applications that required diverse interaction tasks, Ball20 showed strong potential as a general-purpose input device for 3D user interfaces. The integration of haptic feedback, immersive visual icons, and gesture guides enhanced the overall user experience, making the controller more intuitive and immersive. Although the second study's SUS score was slightly below average, the UEQ results for user experience were mostly very high.

With this work, we have demonstrated how a spherical tangible device can serve as a general-purpose input controller, rather than being limited to specialized scenarios. We hope such spherical tangible devices will continue to evolve and be adopted more widely as practical input devices for various interactions.

Acknowledgments

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