Manipulating Virtual Objects in Augmented Reality Using a New Ball-Shaped Input Device

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ABSTRACT

Today's Augmented Reality (AR) technology allows users to explore the real world enriched with digital artifacts, learn from it, or shape it (i.e., creating your own virtual objects). To properly use virtual objects in AR space, users must be able to manipulate them (i.e., rotate or move them). The prerequisite for manipulation is an intuitive interaction technique controlled by an input device. To explore novel AR interaction techniques, a new ball-shaped input device called BIRDY is combined with the HoloLens for the first time.

This paper presents findings regarding this combination of devices. Four new interaction techniques were designed that benefit from BIRDY's orientation invariance. Aiming to identify promising interaction rules, a prototype was developed to evaluate these interaction techniques. Results indicate that using gravity as a placement tool and separating the degrees of freedom when manipulating virtual objects provides the best experience for users. Findings further confirm the potential of using ball-shaped devices for interaction in AR.

CCS CONCEPTS

• **Human-centered computing → Interaction design theory, concepts and paradigms**; **Mixed / augmented reality**; *Haptic devices*; *Gestural input*; Sound-based input / output.

KEYWORDS

3D interaction, AR, manipulation

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1 INTRODUCTION

Augmented Reality (AR) is a technology that allows enriching the physical world with digital artifacts. It can be visually perceived using displays or projections and manipulated using specific controllers. When designing a virtual environment embedded into the real world, it is possible to interact with or manipulate the stereoscopically displayed virtual objects as desired. The established AR platforms – like HoloLens[1] – allow new controllers to be integrated in order to design novel interaction techniques.

The more direct and intuitive the controller interaction is perceived, the deeper the immersion in the digital environment [29]. Numerous controllers have been developed for both research and industry (e.g. tangible input devices [6] and VR controllers), but none of them provide the characteristic of *orientation invariance*. For some purposes, orientation invariance might be a potential improvement over using controllers with defined orientation: digitally exploring round structures such as virtual planets in AR or passing controllers to friends more easily in multi-user scenarios.

2 BIRDY AS AN AR INTERACTION DEVICE

Figure 1: BIRDY placed in its induction charging base and while being using in hand.

[1]https://www.microsoft.com/en-us/hololens

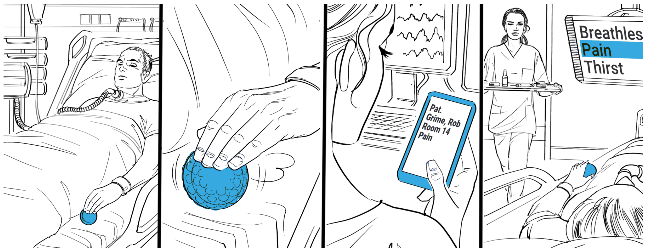

Figure 2: BIRDY's original application: an ICU patient interacts with the ACTIVATE system (drawn by Kai Simons).

The ball-shaped interaction device BIRDY (see Figure 1) was developed within the BMBF-funded research project ACTIVATE[2]. It is specifically designed for the intensive care unit [15, 16]. BIRDY's original application area is screen interaction in *Augmentative and Alternative Communication* for patients who are hindered in verbal communication (see Figure 2). To enable mobile use, the battery-powered device is wirelessly charged and connected.

Prior to this work, BIRDY was neither used to manipulate virtual objects nor applied in the context of AR. However, an explorative study revealed that participants tended to spontaneously interact playfully with the soft BIRDY device when holding it in their hands. Performed actions were, for instance, rotating, shaking, and pressing the device [30]. This opens up a design space far bigger than just ICU patients interacting with screens. BIRDY can detect these gestures using its built-in sensors. They include a sensitive pressure sensor and an inertial measurement unit (IMU), which also consists of a three-axis magnetometer. In addition to these input channels, BIRDY provides multimodal feedback: on the one hand passively due to its elasticity and texture, and on the other originating from a vibration motor, colored LEDs and a buzzer.

As these sensors and actuators resemble conventional VR/AR controllers BIRDY should capable of being used in AR by connecting it wirelessly to an AR output device like the HoloLens. Thus, BIRDY could be used to manipulate virtual objects placed in front of users in the real world (see Section 6.2 for an example setting).

3 RELATED WORK

Before AR technologies entered the consumer market, virtual object manipulation was a common technique integrated into applications, e.g. for CAD modeling or animating movies. This section provides an overview of how virtual objects can be manipulated in 3D spaces and about ball-shaped interaction devices similar to BIRDY.

3.1 Manipulating Virtual Objects in 3D Spaces

Whereas the combination of ball-shaped input devices and AR is not a well-researched field, the manipulation of objects in 3D space with various controllers is already well examined. Findings from research on mid-air gestures [2, 20–22] or Vive controllers[3] [22] can be adapted to this emerging research area by incorporating them into this work's interaction design.

Furthermore, many solutions proposed in literature either use AR on 2D screens (smartphones, projectors, monitors) [19, 24] or stereoscopic devices (VR headsets, 3D displays) [21, 22, 32] as a visual output. Although the output medium differs, these findings are relevant and useful for AR-related research questions.

To the best of our knowledge, we are the first to analyze the combination of ball-shaped input devices and AR. The insights and concepts referenced above provide a valuable foundation for defining rules of interaction in this research (see Section 4).

3.2 Ball-Shaped Interaction Devices

There are several devices similar to BIRDY featuring a ball shape, wireless use, and light-weight hardware with internal sensors [1, 23, 25, 28, 31]. These devices were combined with desktop or mobile output devices instead of immersive AR technology. Most of these devices share similarities with BIRDY, but usually lack specific input channels. For instance, only BIRDY uses the concept of being squeezed as an input gesture. The most similar devices to BIRDY are PALLA and Roly-Poly Mouse, both not designed for AR use.

The spherical input device PALLA was designed for leisure activities and video gaming [31]. It is based on sensors similar to those used in BIRDY and also provides simple feedback based on a vibration motor and a LED indicator light. As with BIRDY, PALLA's robust design allows worry-free interaction without the risk of damaging anything, but features a rigid sphere body.

The ball-shaped Roly-Poly Mouse (RPM) [25] was inspired by a roly-poly toy that moves back after being tilted due to its low center of mass. Unlike BIRDY, RPM lacks actuators making it incapable of providing any user feedback. Furthermore, RPM has a ring button but is not deformable and thus cannot be squeezed. It was designed for 2D-based object selection and 3D interaction.

4 INTERACTION DESIGN

Designing AR interaction for ball-shaped devices requires a set of atomic rules. This section describes concepts for four different interaction techniques. All of them are based on a set of *common rules* (described in Section 4.1), while they differ in a unique set of *additional rules for assessment* (described in Section 4.2).

While the majority of the rules were designed following the findings of the research community, a design workshop with experts was conducted to evaluate and revise these rules if necessary. During the two-hour workshop, interaction design experts critically discussed interaction patterns to explore new opportunities concerning the specific combination of BIRDY and AR.

4.1 Defining Common Rules

Direct Manipulation There is a direct link between the input device and the virtual object. Changing the position or orientation of the input device has an immediate impact on the virtual object. This is very common for interaction devices and provides a natural feeling for users [11]. Since this is the only way the user can manipulate objects, there is no quick undo action.

Scaled Manipulation Mendes et al. proposes guidelines for 3D object manipulation which recommend using scaled transformations to improve placement precision [21]. Instead of using a one-to-one mapping, the translation impact is modified by an intelligent scaling algorithm: The *PRISM* algorithm improves precision during fine adjustments and assists with large-sized translations [10]. The

[2]https://projekt-activate.de/en/about-activate/
[3]https://www.vive.com/eu/accessory/controller/

translational impact on the virtual object is regulated according to the user's intention, which is derived from the speed of the device's motions. Fast movements thus lead to translations in a much larger range, while slow motions reduce the translation. This may also prevent errors and user frustration caused by noisy sensor data or by unintentional shaking while squeezing the device.

Juicy Feedback User feedback will adhere to the gamification term *Juicy Feedback* [13]. All interactions, the virtual object itself, and the AR space provide user feedback that is rich, inviting, fresh, and coherent. The feedback channels are multimodal incorporating actuators of the interaction device and the AR headset to explain the state of the AR space descriptively. Collision of the virtual object with real-world geometry are announced by spatial sound, visuals, and vibration.

Sonification Special auditory cues are used to convey additional information during the interaction as defined in the *Sonification* principle [27]. This will be adopted as follows: During manipulation, a repeating sound cue is playing. This sound cue then shifts its pitch according to the translation velocity with the intention of improving precision by giving users a sense of speed.

4.2 Additional Rules for Assessment

Three rules for assessment were defined. The interaction techniques described in Section 4.3 differ in which of these rules they apply.

Separation of DOF & Ratcheting Most manipulation tools are based on manipulating virtual objects in six degrees of freedom (DOF): rotating around the three main axes and translating along them. Several tools offer a separation of rotation and translation in two modes [10, 19, 21, 22, 24, 25, 32]. Fundamental research of Chen et al. showed that manipulating all six DOF simultaneously leads to better results [5]. Since then, however, some improved interaction techniques with separated DOF resulted in better performance [10, 21]. This rule can be implemented in two distinct ways:

(a) While exerting pressure on the input device, users manipulate the object in all six DOF simultaneously. Lowering the pressure stops the object's manipulation. This allows users to reorientate and reposition the input device without having to fear to start a second manipulation action. This concept is called *ratcheting* [11, 32].

(b) Manipulation of a virtual object is carried out in two separate modes: translation and rotation. These modes can be switched using voice commands. The translation mode works as described in (a). As long as users remains in rotation mode, the rotation input is transferred directly to the virtual object without the need for ratcheting. Users may change their grip on the input device to turn the object by large-sized angles. Also, it is not necessary to rotate the device back to its starting orientation due to the device being orientation invariant [12, 26].

Force of Gravity The object behaves as if users were to physically pick it up and then drop it. During the interaction, the virtual object is handled according to direct manipulation. As soon as the interaction ends, the object falls to the ground under the influence of gravity. A physics simulation confers mass to the virtual object in addition to a slight bounciness. The simulation stops again as soon as users manipulate the object a second time.

Collision With World Geometry Users handle the virtual object as usual, but are restricted in their manipulation by the surrounding space. The object collides with the real-world geometry, preventing users from moving it through walls, the ceiling, or the floor. This rule can be seen as a tool of assistance utilizing the constraints of the real world.

4.3 Proposing Four Interaction Techniques

By combining different sets of rules, four distinct interaction techniques were designed: *Integration Interaction Technique*, *Collision Interaction Technique*, *Gravity Interaction Technique*, and *Separated Interaction Technique*. As stated earlier, each interaction technique is based on the common rules. Table 1 shows how the interaction techniques differ and which ruleset is applied in which manner.

Table 1: Difference between interaction techniques regarding the three rules for assessment.

Diffence in implementation of assessment rules			Resulting interaction technique (InT)
Separation of DOF & ratcheting	Force of gravity	Collision with world geometry	
Manipulate all 6DOF simultaneously, ratcheting	No gravity	No collision	*Integration InT*
		Collision	*Collision InT*
	Gravity	No collision	Not feasable[4]
		Collision	*Gravity InT*
Manipulate translation and rotation in two separate modes, without ratcheting	No gravity	No collision	*Separated InT*
		Collision	Not feasable[5]
	Gravity	No collision	Not feasable[4]
		Collision	Not feasable[5]

5 IMPLEMENTING A DEMONSTRATOR

A demonstrator was implemented allowing users to manipulate a virtual object using one of the four proposed interaction techniques. The demonstrator consists of five components (see Figure 3). Each performs a specific set of tasks while communicating via Bluetooth, Wi-Fi, or Ethernet. The three main software components are the *demonstrator app*, the *link app*, and the *cockpit app*.

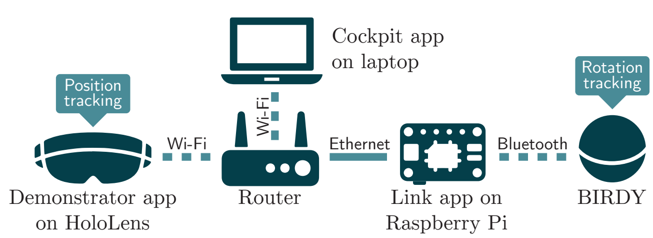

Figure 3: System architecture of the demonstrator.

[4] Without collision, the force of gravity would let virtual objects fall through the floor.
[5] In some instances, the collision can prevent the separated rotation mode from working when a virtual object is near colliding geometry.

5.1 AR Setup With HoloLens and BIRDY

Microsoft's HoloLens glasses are used to generate the AR environment allowing users to interact with 3D projections. The AR glasses scan the surrounding space to create a detailed, geometric room model using an onboard SLAM algorithm [8] that provides a coordinate system for the demonstrator. The challenge of tracking BIRDY during the AR interaction can be separated into two subtasks: tracking BIRDY's rotation and tracking its position.

Using BIRDY's sensors (see Section 2), its orientation can be calculated using sensor fusion. The demonstrator utilizes the Madgwick filter [18, 33, 34], which fuses the acceleration data, angular velocity data, and magnetic readings from BIRDY to determine how users rotate the device. The same approach was previously taken in the PALLA project [31]. After an initial calibration, BIRDY's orientation in relation to the AR scene can be calculated.

Tracking BIRDY's position by using its internal sensors as the only data source does not yield usable tracking information. Calculating positional changes solely with IMU sensor data (also called dead-reckoning) results in significant, cumulative errors while approximating the device's position [14, 17]. These errors prevent a sufficiently precise enough tracking for AR interaction.

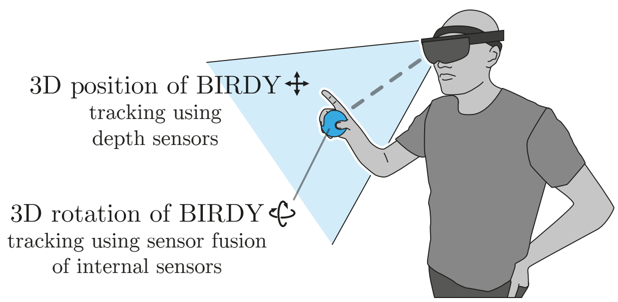

Figure 4: A user interacting with the position and rotation tracked BIRDY while wearing HoloLens.

In an alternative approach, the demonstrator uses HoloLens' hand-tracking capabilities to track BIRDY. HoloLens can detect the user's hand position in front of its build-in depth sensors (which are typically used to detect mid-air gestures). Holding BIRDY with the arm angled as displayed in Figure 4 allows HoloLens to precisely determine BIRDY's relative positioning to the headset. Combined with the headset's approximated position within the room, this enables the mapping of BIRDY's absolute position in the AR scene.

If technical tracking issues impair the tracking quality, users will be notified while providing a way to solve the problem.

5.2 Main Software Components

Demonstrator App The key component of the demonstrator system consists of a Unity[6] application deployed on HoloLens. It is written in C# utilizing the Windows 10 SDK using Microsoft's Universal Windows Platform. Aside from creating and rendering the 3D scene for the AR overlay in real-time, it also handles the network communication, speech recognition, and logging. Furthermore, it controls the interaction logic as defined in the four designed interaction techniques (see Section 4.3).

[6]https://unity.com/

Link App HoloLens establishs a connection to BIRDY via a relay component deployed on a Raspberry Pi computer. A C++ application running in a Linux environment pre-processes the sensor data (for instance, dealing with sensor fusion). To connect with BIRDY via Bluetooth, a library of BIRDY's hardware manufacturer CogniMed[7] is utilized. Furthermore, the link app allows for easy and quick switching to spare BIRDY devices when the internal battery is depleted, without having to change the configuration on the HoloLens headset itself.

Cockpit App The demonstrator provides a separate cockpit control panel for allowing the experimenter to actively guide the user and change the AR scene when necessary. Using the cockpit, the experimenter can access the demonstrator app and the link app remotely. In addition, a logging component was implemented to capture detailed user data.

6 QUASI-EXPERIMENTAL STUDY

The demonstrator was used in a quasi-experimental study to evaluate the interaction techniques described above.

6.1 Participants

Twelve participants (five female, seven male; one left-handed, eleven right-handed) tested the interaction techniques. They did not know about the BIRDY project beforehand. The average age was 26 years (SD = 4.67). Five participants normally wear glasses. While four of them refrained from using their glasses due to making it uncomfortable to wear them with HoloLens, the other one used contact lenses. Nine participants reported that they had experience in interacting with AR environments. Five of them used HoloLens for the first time. The participants showed a high affinity for technology interaction [9] with an average ATI score of 4.90 (SD = 1.00; scale ranges from 1 (low affinity) to 6 (high affinity)).

6.2 Task & Setting

As the interaction techniques cannot be used without a pre-defined context, a simple docking task was designed. Visual menu systems were not used, allowing non-disruptive interaction with the AR environment and avoiding unnecessary overlays.

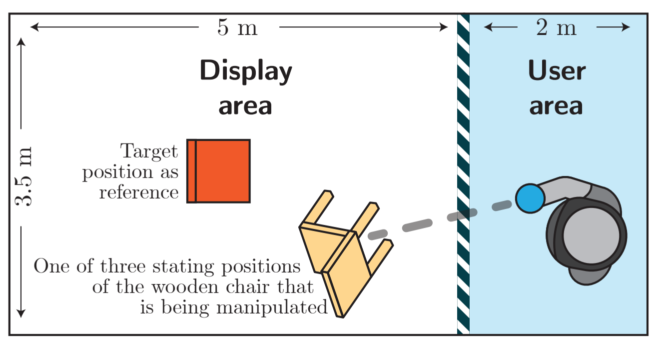

Figure 5: Ground plan of the evaluation setup.

The task [8] takes place in a rectangular room, divided into the display and user area (see Figure 5). Participants stand in the user

[7]https://www.cognimed.de/index.php/en/
[8]As shown in this video: https://youtu.be/I0KefFdKU_U

area ready for interaction wearing HoloLens and holding BIRDY in their dominant hand. While projections are visible in the display area, the real world is free of obstacles. Participants are allowed to move freely in the user area, yet prohibited from stepping into the display area. A virtual red chair is projected into the center of the display area (3 m in front of the user), which serves as a reference for the target position and rotation for solving the docking task. Chairs were chosen as the manipulation object as their orientation is easy to identify and their target position seems clear. When starting the task, the user sees an additional chair floating in the air with seemingly random placement (see Figure 6). This chair can be manipulated using BIRDY. Using one of the interaction techniques, the participant rotates and translates the chair aiming to align it congruently with the red reference chair. This should be done both fast and accurately. The task is finished when the participant thinks the chairs connect, which is when they should inform the experimenter.

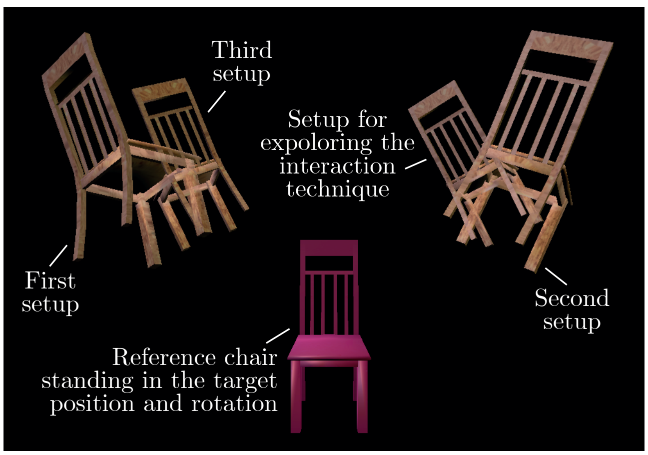

Figure 6: All starting positions and orientations of the movable wooden chair and the reference chair below them.

6.3 Instruments

To evaluate the quality of the interaction techniques, seven target requirements were specified (see Table 2). Requirements I to III are closely related to the universal ISO 9241-11 framework [7] and serve as abstract foundation guidelines. To ensure valuable user experience of the specific purpose of object manipulation, four additional requirements (IV to VII) have been added to emphasize vital conditions similar to other research projects [4, 31]. The following utilized instruments for measuring were selected, as they provide rich data regarding the defined requirements:

(1) a usability questionnaire for each interaction technique, based on the SUS scale [3] and expanded with additional items (sources, see Table 4), to test for the requirements described in Table 2,
(2) observation notes, taken during the interaction,
(3) an automatically generated log file of user actions provided by the demonstrator,
(4) a demographic and custom-made questionnaire, and
(5) the ATI questionnaire [9].

Table 2: Requirements for interaction techniques.

No.	Name	The interaction technique …
I	Effectiveness	…provides tools to manipulate a virtual object by translating and rotating it.
II	Efficiency	…is taking up minimal time while not straining users mentally or physically.
III	Satisfaction	…leaves users with a positive mood towards the system.
IV	Intuitiveness	…is easy to learn while not needing many initial instructions.
V	Mental cost	…provides help by assisting users in solving a task and not being complicated.
VI	Fun	…is satisfying to use to an extend that induces toying with it and being enjoyable.
VII	Precision	…provides the necessary precision for fine adjustments.

6.4 Design & Procedure

A within-subject study design was used. The participants were instructed about the procedure and had time to playfully explore HoloLens to get used to the AR environment. As the total number of participants was not known in the beginning, the test order was not counterbalanced, but randomized to prevent learning effects due to increased familiarity with AR interaction. Each interaction technique was tested as follows: After introducing and exploring the specific interaction technique, the participant solved the docking task three times. To minimize the learning effect caused by familiar starting properties, every task iteration used a different starting position and orientation (see Figure 6). While the starting properties seemed like random setups to the participants, they were deliberately chosen to have a distance of 1.5 m to target position and 152° to target rotation. This ensures having a task with the same difficulty while still necessitating a different solution path. After testing an interaction technique, the participants filled the usability questionnaire for that technique.

At the end of the study, they completed the ATI, demographic, and custom-made questionnaire.

6.5 Results

In the following, the explicit user ranking of the interaction techniques as well as their performance and usability results are presented. While these data are derived from the recorded log and self-reports, the additional study observations are also described.

6.5.1 Ranking of Interaction Techniques. In the concluding custom-made questionnaire, the participants were asked to rank the tested interaction techniques by preference. Counting the participants' favorites, the ranking results as follows:

(1) Gravity Interaction Technique (four votes)
(1) Separated Interaction Technique (four votes)
(2) Integration Interaction Technique (three votes)
(3) Collision Interaction Technique (one vote)

Table 3: Performance comparision between interaction techniques (InT), N = 12 with each three repetitions.

	Integration InT		Collision InT		Gravity InT		Separated InT	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Position error	3.30 cm	1.81	3.85 cm	1.84	4.95 cm	2.93	2.76 cm	1.71
Rotation error	5.97°	2.61	6.44°	4.35	6.22°	4.08	5.20°	2.92
Task completion time (TCT)	65.74 s	44.18	54.83	31.1	55.85 s	33.85	72.52 s	46.54
Part of TCT actively manipulating	77.78%	8.07	77.08%	10.16	68.59%	7.80	78.98%	6.24
Number of interactions	12.91	9.66	11.14	8.64	10.89	7.49	8.58	4.44

6.5.2 Performance Results. To compare the performance of the interaction techniques, the automatically recorded log was used to calculate details like precision as in *position error* and *rotation error*. These error values measure the distance in 3D space between the participants' solution and the given target properties. Furthermore, the *task completion time* was calculated. It measures the time between the auditive cue notifying participants that the task begins and the time when they were satisfied with their performance and inform the experimenter.

For a detailed performance comparison between the interaction techniques, see Table 3. The standard deviation of the position errors is highest for the *Gravity Interaction Technique*, while the *Separated Interaction Technique* has the lowest deviation. The precision resulting from the *Collision Interaction Technique* was descriptively worse than from the *Integration Interaction Technique*. In general, participants achieved the best precision using the *Separated Interaction Technique* (low position and rotation error). However, users took 14 s longer to solve the task compared to the average task completion time of the three alternatives (combined $M = 58.67$ s, $SD = 36.46$). While using the *Separated Interaction Technique*, the participants changed between rotating and translating 8.58 times on average (*SD* 2.62) and stayed in the rotation mode for 20.8% (*SD* 17.05) of the task completion time.

6.5.3 Observations & Usability Results. The participants instinctively started playing around with the device. During manipulation, three participants actively roamed around in the user area aiming to perform larger translations and even bending their knees to get into a lower position. On the other hand, three other participants leaned against the user area's back wall to counteract muscle fatigue. After ten minutes, one of them even supported his arm with the free hand. One participant suggested using a different sound cue for the translation's sonification, as they did not like it. Two participants complained about HoloLens' restricted field of view as it impedes finding the virtual object in the AR space.

The differences regarding the usability of the individual interaction techniques are shown in the questionnaire results in Table 4.

The *Integration Interaction Technique* was explicitly praised by two participants for not restricting manipulation in any way and giving users full control. It allowed them to move the object along arbitrary manipulation paths. Four users described the technique as similar to the *Collision* and the *Gravity Interaction Technique*, yet without limitations.

The *Collision Interaction Technique* gave the participants a tool of assistance. Two users praised how much easier translating the object is, considering it helpful. The two users further noted that the collision impedes the rotation ability. One participant described the collisions as hindering.

The *Gravity Interaction Technique* was consistently described as natural. The majority of the participants expressed having more fun and being immersed more deeply by seeing the object behave in line with expectations as it is affected by gravity and collisions. This interaction frequently resulted in the problem for each participant that the chair fell over on its side. The chair then had to be rotated 90° in one continuous rotation to put it upright again. Three participants remarked that the ratcheting principle is not working well in this situation as it drops the object to the ground when letting go. One participant utilized this behavior by spontaneously picking up the chair and dropping it until it randomly fell into a desired position and orientation. Fine adjustments sometimes worsened the result.

Considering the two modes of the *Separated Interaction Technique*, all participants stated they liked being able to translate the object without accidentally rotating it. This resulted in more vivid manipulations making more use of the scaling PRISM algorithm since the users were not afraid of manipulation mistakes. Fine adjustments were less error-prone. One participant did not like the mode change as he perceived it as complicated. They preferred the other techniques because they gave them faster results. Another participant tried intuitively to separate rotation from translation, even while using the three alternative interaction techniques. This participant liked the way the *Separated Interaction Technique* is supporting their natural way of problem-solving. Another person mentioned that the separation lowers their mental strain. Consistently, the ratcheting-less rotation mode was preferred. Furthermore, there was no risk of hand muscle cramps, which was a problem of the alternative interaction techniques that require pressing BIRDY for rotating.

6.6 Discussion

Each participant quickly adapted to BIRDY as an AR interaction device. Tactile and auditory feedback was understood as an indicator of successful input. With regard to the room-scale interaction, all four interaction techniques allowed *precise* results, deviating on average less than 5 cm and 7° at a interaction distance of 3 m. Rotation and position errors do not differ much among all interaction techniques which illustrates the techniques' *effectiveness*.

As shown in the ranking, the *Gravity Interaction Technique* and *Separated Interaction Technique* were preferred by most participants. Interestingly, both interaction techniques and their results differ considerably.

Table 4: Usability comparision between interaction techniques (InT), scale of 1 to 7, higher values mean stronger agreement, N = 12.

	Integration InT		Collision InT		Gravity InT		Separated InT	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
The system was easy to use.[9]	3.58	0.90	3.83	0.83	3.92	0.9	4.08	0.79
I felt confident using the system.[8]	3.58	1.08	3.67	0.89	4.00	1.04	4.00	0.60
The InT works well for rotating.[10]	2.83	1.03	3.25	1.06	3.17	1.11	3.50	1.09
The InT works well for translating.[9]	3.92	1.08	3.83	1.11	4.08	1.16	4.58	0.51
Switching between rotating and translating was easy.[9]	3.17	1.4	3.33	1.15	3.50	1.31	4.08	1.00
It was easy to master the IT.[8]	4.08	1.08	4.08	1.16	4.08	1.16	3.83	0.72
The InT was intuitive.[9]	4.33	0.98	4.33	0.78	4.42	0.79	3.92	0.79
The InT required a lot of tact and sensitivity.[8]	3.83	1.11	3.92	1.24	3.08	1.31	3.58	1.44
The InT required a lot of concentration.[8]	3.83	1.27	3.58	1.16	3.58	1.16	3.75	1.29

The *Gravity Interaction Technique* provides the most inaccurate results of all techniques. However, the participants had the most *fun* utilizing gravity as a assistive tool with feedback that mapped the state of the AR environment in a consistently *satisfying* way.

Meanwhile, the also prefered *Separated Interaction Technique* allowed the highest *precision*. This indicates that the separation of rotation and translation is more precise than a simultaneous 6DOF manipulation. This is in agreement with previous research of the advantages of separated degrees of freedom [10, 21]. A favoring factor for the participants' preference might include the rotation by changing the grip on BIRDY, which resulted in less strain on the wrist due to the elimination of the ratcheting principle. Also, the two separate modes supported the *intuitive* way of thinking when manipulating the virtual object which also reduces the *mental cost*. The separating of rotation and translation further leads to a longer task completion time, thereby reducing the interaction technique's *efficiency* compared to the other techniques without DOF separation.

Overall, this shows a tradeoff between *intuitiveness* – provided by the *Gravity Interaction Technique* – versus *precision* – obtainable using the *Separated Interaction Technique*. Based on the individual taste, AR users with ball-shaped input-devices could either prefer being more precise or having a more intuitive interaction.

The separated rotation principle, where BIRDY is turned by changing the grip, allowed manipulations with far fewer necessary interactions compared to pressing the device multiple times to rotate by ratcheting. Combined with the risk of hand cramps due to pressing of the device while ratcheting, a separated rotation mode might lessen hand and arm fatique remarkably.

Considering the precision of the *Collision Interaction Technique* was not better than the alternatives, the use of collision alone in interaction techniques might be more of a burden than an assistance. In this study, the concept of collision with real-world geometry did not improve precision.

As desired by two participants, a new mixed interaction technique consisting of the most promising rules of both techniques (separated rotation and translation combined with gravity force) should be investigated further. The beneficial characteristics of a physics simulation could thus be used as a kind of tool for placement on surfaces.

6.7 Contraints, Restrictions & Proposed Solutions

To improve the user experience, HoloLens' limited field of view can be compensated by choosing different AR hardware with an extended display for virtual objects (e.g., Varjo XR-3[11] and HoloLens 2).

Furthermore, the mentioned muscle fatigue stemming from the interaction techniques should be considered and counteracted. An alternative more stable method of tracking BIRDY's position may be used to avoid unnecessarily constraining users' arm postures.

In general, users required a considerable amount of time to complete the tasks using the prototypical implementation of the interaction techniques in the demonstrator. In a further step, an improved demonstrator can be implemented using high-performance computers (instead of the HoloLens on-board computer) to improve both responsiveness and interaction quality.

7 CONCLUSION

This paper investigated how users can manipulate virtual objects in AR using ball-shaped input devices. Using BIRDY as a rich input and output device, it was shown that it can be used as an AR controller and provides unique opportunities other devices lack, e.g. its orientation invariance and being squeezed as an input device.

To investigate the opportunities in detail, a ruleset for interaction techniques has been defined. A framework consisting of four common rules for ball-shaped object interaction in AR has been proposed. With the additional rules for assessment, four distinct interaction techniques were defined and implemented in a prototypical demonstrator.

To evaluate the feasibility of ball-shaped interaction, a quasi-experimental user study was conducted with this demonstrator. Using BIRDY as a controller and HoloLens as the AR device, results indicated that *gravity* and *separated rotation and translation* showed the most promising effects. A tradeoff between intuitiveness and precision became apperent.

This opens a wide design space for applications and studies on specific contexts based on this research. Since all manipulations in

[9]Item from or based on the SUS scale [3].
[10]Additional item for testing requirements of Section 6.3.
[11]https://varjo.com/products/xr-3/

this study were designed for one-handed execution, the benefits of two-handed or even multi-device input using both hands can be assessed [4, 11] as well as multi-user scenarios.

An additional logical next step might be investigating a mixed interaction technique using *separated rotation and translation* with an additional *gravity tool mode* as proposed by two study participants.

Furthermore, the difference in varying gravity accelerations can be tested, as well as other precision algorithms besides PRISM. Using context-sensitive precision algorithms to help users solve tasks in specific environments can further improve performance.

As AR technology continues to advance and becomes available to a broader market, the question of appropriate input devices and how they should work needs to be anwsered. The improvements and new features of next-generation AR devices should be utilized to compare the proposed design rules for ball-shaped interaction with competing conventional controller interaction techniques in the entertainment industry.

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