Encountered-Type Tabletop Haptic Display for Objects On-Demand in Virtual Environments

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***Abstract*— This paper presents the design and capabilities of a custom-built Encountered-Type Haptic Display. With an X-Y-Z-Yaw plotter mechanism below the tabletop and four permanent magnets in the end-effector, the device can manipulate multiple objects in three dimensions on top of the table. Four hall effect sensors in the end-effector are used to compensate the friction of the display and increase the positioning accuracy of objects to 0.5 mm. With an end-effector speed of 66.6 cm/s, objects can be placed in a workspace of 47.2×26 cm. The device is built for human-computer interaction scenarios in virtual reality (VR) and augmented reality (AR) to provide haptic feedback on-demand. Due to the design, arbitrary object shapes and materials can be presented to the user within the table's workspace. The usability and performance of the table are evaluated with a user study.**

I. Introduction

Using the sense of touch to explore and perceive our environment is a crucial skill for human beings. From a young age, we learn to use this sense and gather information about all kinds of objects, materials, and physical properties [1]. In virtual environments, haptic feedback is often substituted with visual or audio stimuli, giving the user the illusion of interacting with the digital world. However, Encountered-Type Haptic Displays offer a more tangible and immersive approach. These innovative haptic systems provide users with the capability to physically feel and interact with virtual surfaces and objects. Mercado et al. [2, p.2] define an Encountered-Type Haptic Display as *"a device capable of placing a part of itself or in its entirety in an encountered location"*. The definition covers both non-wearable devices and wearable devices without constant contact with the user's hand. One advantage of the former is that the user experience can be enhanced by providing hands-free interaction capability. Additionally, it enhances hand tracking since there is no obstructive device present. The disadvantage of non-wearable devices is that the haptic feedback is usually limited to flat surfaces or singular contact points [3, 4].

In this paper, we focus on this limitation and devise an idea to present 3D haptic displays. We designed and built an Encountered-Type Haptic Display with magnetically actuated object movements that allow multi-object surface presentation through attaching and detaching various shaped objects together with tactile sensing to perceive interactions. This device can be used for various scenarios, such as in further scientific studies, for rehabilitation, or for gaming.

Fig. 1. The Encountered-Type Haptic Display. A custom-designed X-Y-Z-Yaw plotter is attached below the table, capable of moving objects on top of the table with magnets in the end-effector and the object.

The contribution of this work can be summarized as follows: Development of an Encountered-Type Haptic Display for Virtual and Augmented Reality, as well as other human-computer interaction scenarios, with a three-dimensional movement (x, y, and yaw) of arbitrary objects on the tabletop.

The remainder of this paper is structured as follows. Section II describes the work related to the paper at hand. The design of the haptic display is described in Section III, first the requirements, then the hardware and software used to fulfill them. Furthermore, some features are presented in this section. The following section evaluates the haptic display in a user study, to assess its capabilities and the resulting usability. In Section IV-C, we discuss the results of the experiments. The last section concludes the paper.

II. Related Work

The work related to the paper at hand can be divided into two parts: Encountered-Type Haptic Displays for virtual environments and the technical part, magnetic actuation.

A. Encountered-Type Haptic Displays

Encountered-Type Haptic Displays (ETHDs) are used in virtual environments to provide haptic feedback for the

*This research was funded by the German Research Foundation (DFG) and the National Science Foundation of China in the project Crossmodal Learning, TRR-169.

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user. Mercado et al. [2] give an overview of the history, definitions, and current state of the art in the field of haptic feedback. We can divide ETHDs into two categories, grounded and ungrounded devices. Grounded devices have a fixed workspace in which haptic surfaces can be presented. In contrast, ungrounded ones are not fixed to a position. A common approach for grounded ETHDs is robotic manipulators presenting a haptic surface. The design has the advantage of providing feedback with 6 Degrees of Freedom. Devine et al. [5] used a Baxter robot to present a flat surface to the user wearing an HTC Vive. In a user study, the participants pushed with Vive controllers against the haptic surface and felt different weighted boxes. Mercado et al. [6] only used a Vive tracker to trace the user's hand position. In their use case, the participants observed a flat haptic surface presented by a UR5 robot. The users could perceive the surface with one finger instead of a controller. In both works, the haptic feedback is restricted to singular contact points and flat shapes.

An interesting approach to presenting various shapes is by providing lateral and kinesthetic feedback with shape-displays [7, 8]. Arrays of actuated square pins with adjustable height positions create explorable shapes. Mounted on an omnidirectional platform, these displays can be positioned anywhere in the room to provide on-demand feedback to the user. The disadvantage of these devices is the resolution of the rectangular shape of the pins. Gonzalez et al. [9] presented an approach comparable to our table. They use a desktop-scale omnidirectional mobile robot moving on a table to present a haptic surface to the user.

Additionally, 3D button representations in VR and matching real buttons providing passive haptic feedback were found effective in achieving meaningful interactions with high user acceptance [10].

B. Magnetic Control

Magnetic control is a popular research field for nanoparticle manipulation [11, 12, 13]. The two main applications in this field are nanoparticle sorting and separating them from a mixture. Abedini-Nassab et al. [11] summarize the most common methods for particle manipulation: (i) with an external permanent magnet or electromagnet, (ii) with embedded micro-wires and micro-coils, and (iii) with embedded magnetic thin films. In nanoparticle dimensions, permanent magnets or electromagnets are rather used for particle manipulation in laminar flows to separate particles [14] or for microfluidic mixing by rotating magnetic particles [15] than for x-y movements as the dimensions are too small. For planar movements, either micro-coils or embedded magnetic films could be used. Both techniques require more complex engineering and hardware design than the permanent version. A larger approach, similar to this work, is the commercially available Atari pong table that brings the popular 70s arcade game to a mechanical version [16]. The table uses similar technology as our device, with a two-axis system below a surface and a magnet controlling the ball on top of the tabletop. In contrast to our work, they can neither detach nor rotate the object. Furthermore, they do not gather information about the ball on the surface.

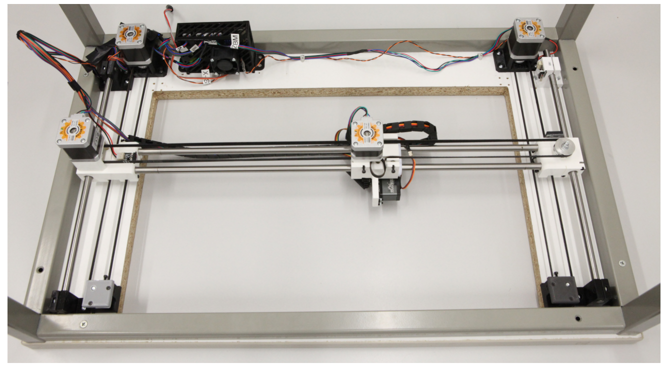

Fig. 2. The underside of the haptic display. Two stepper motors actuate the shorter y-axis and one controls the longer x-axis. A fourth motor actuates the yaw rotation, and a servo motor the z-axis within the end-effector.

III. The Haptic Display

A. Design

The table is designed for various human-robot interaction applications and scenarios in virtual environments. In a typical use case, a user will interact with arbitrary virtual objects on top of the table in VR, perceive the shape and material, manipulate, or move them. This case covers a lot of requirements for the device. It is essential to move and place objects to specific locations on the table and present a 3D surface "on-demand" for the user, meaning a movement in x and y directions and rotation for objects without a circular symmetry. Furthermore, to allow multi-object manipulation, it is necessary to attach and detach objects. The haptic device should be reliable to maintain the illusion, meaning the device should detect when the physical object is at a wrong position and recover it to the location of the virtual object. As the interaction should not be distracted by any visible mechanical parts, the display has to look and feel like a regular table at first sight, including that the user can sit at the table without restrictions. This is more important in augmented reality scenarios than in virtual ones. A less stringent requirement pertains to the size of the workspace, as the table is scalable, allowing the creation of a larger version with an expanded workspace if necessary.

1) Hardware: Figure 1 and Figure 2 show the final version of the Encountered-Type Haptic Display. The basis of this device is a belt-driven X-Y plotter design often used in 3D printing, screwed below a standard table. In this case, we used a table with a width of 80 cm and a length of 50 cm, resulting in a maximum workspace of 47.2 by 26 cm. To increase the workspace, a larger table and longer guides can be used. The axes are assembled as shown in Figure 2, with two parallel guides attached at each end of the tabletop for the y movement and two guides attached to the previous ones for the x movement. To control the y-axis, two stepper motors are used, which are fixed to the upper right and upper

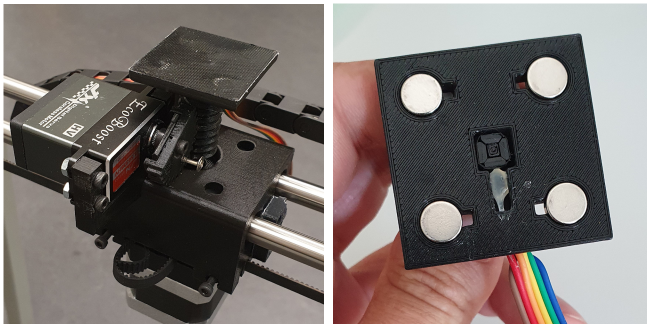

Fig. 3. (left) 2-DoF end-effector, a combination of a revolute and prismatic joint. The tool can be rotated by a stepper motor and moved up and down by a servo motor. (right) Four Hall sensors are integrated into the center of the tool to measure magnetic fields from the other side of the surface.

left corners. The stepper motor that controls the x movement moves with the whole axis on the y-guides. A fourth stepper motor on the end-effector controls the rotation, and a servo motor moves the tool up and down on the z-axis to attach and detach objects. Overall, the table has 4-DoF, x, y, z, and the yaw rotation below the table and 3-DoF on top of it without the z movement. The custom-designed end-effector can be seen in Figure 3 on the left image. It combines 2 Degrees of Freedom (DoF) in one axis of motion. With this configuration, we achieve speeds of up to 100 cm/s per axis. With an attached object, we achieved reliable movements at a speed of 66.6 cm/s. External factors such as temperature and humidity led to issues at higher speeds. Motors, servo, and endstops are controlled by a Bigtreetech SKR mini E3 V2.0 mainboard, a standard 3D printing board with integrated motor drivers. To attach objects to the end-effector, four magnets are fitted to the corners of the tool (see Figure 3 right). The object on top of the table must have two to four magnets fixed at the same positions as the tool, so that the rotation is transferred to the object. With only one magnet, the object would not be rotational stable.

To gather information about the object on top of the surface, we attached an additional magnet centered under the object and four Hall effect sensors [17] in the center of the tool (see Figure 3 right). These sensors measure the reference magnet's magnetic field, which is inverted compared to the mounting magnets. An Arduino Nano reads the Hall effect sensors at 400 Hz. With those sensors, we can estimate the position of the reference magnet and detect interactions or disturbances.

2) Software: As the mechanical design of the table is inspired by X-Y plotters or 3D printers, we use the open-source firmware Marlin [18] to control the table. Marlin is a popular firmware to control stepper and servo motors, endstops, fans, and many other devices like extruders and printer beds, which we do not need for our setup. In Marlin, everything is controlled with G-code commands via a serial or wireless connection. A significant advantage is the availability of many common mainboards, making it easy to transfer our idea to different hardware designs and, therefore, platform-agnostic. The firmware handles acceleration, deceleration, homing, position tracking, etc. However, our scenario differs from the typical use case for Marlin, so we have a few things that need to be improved. As the G-code for 3D prints is generated in advance and all movements are preplanned, there is no need for real-time controlling or replanning, which is a requirement in our scenario. We solved this shortcoming by interpolating movements and sending G-code commands in time, allowing a fast reaction to trajectory changes, e.g., in teleoperation scenarios.

To control the device comfortably, we implemented a robot operating system (ROS) [19] interface that accepts position commands, generates G-code accordingly, and controls the table with a loop rate of 100 Hz. ROS offers many tools for visualization, communication, path planning, etc., so it is an appropriate middleware to integrate the table with other robotic setups and software. Further, there are interfaces to the Unity game engine to integrate the table into a virtual environment.

B. Friction Compensation & Position Detection

Compensating the friction of the object on the table is essential for accurately positioning haptic surfaces. Without friction, the object would always be perfectly aligned with the end-effector. As this is not the case, we tried to reduce the friction as much as possible by attaching a Teflon mat to the object and the end-effector. Still, there is slight friction causing trailing effects of the object on top between 3 to 5 mm. As described in Section III-A.1 we use four Hall sensors to measure the magnetic field of a reference magnet attached to the object. We also tested an MLX90393 3D magnetometer with ready-to-use interfaces and direct x-y-z position output. Unfortunately, the magnetic field of the mounting magnets saturates the output and makes it unusable. As the assembly of the Hall sensors in the end-effector is not accurate enough for mathematical analysis of the position, we use a simple deep-learning approach to estimate the position of the object on top. The network we use has three linear, fully connected layers. The first and third layers have ten neurons with ReLU activation functions, and the middle has 20 neurons with ReLU activation. We tried to keep the network simple and tuned the parameters with hyper-optimization. As loss function, Mean Squared Error is used with an Adam optimizer with a learning rate of 0.0001 and a weight decay of 0.07. The batch size is five, the training-to-test ratio is 70 % to 30 %, and we trained for 100 epochs. We recorded 24000 position samples in a 6 mm radius around the end-effector center and reached a test accuracy of 0.5 mm with our deep-learning approach.

C. Object Recovery

The attached object may get lost on the table. Reasons for this include intended or unintended human interaction, high friction, or too high speeds. Based on previous tests, we have identified that losing the object without human interaction is only a minor issue. However, we aim to enhance the table's robustness as much as possible. To achieve this, we implemented an object recovery feature that utilizes conventional computer vision techniques. First, we begin by binarizing the image using the color of the tabletop as a threshold and perform edge detection and identify the table's surface. We then apply clustering of the black pixels, determine which clusters are within the workspace, and assign them to known and unknown object positions. In that way, we can detect misplaced objects and recover them.

D. Interaction Detection

Interaction detection includes determining if the object has been taken away or touched. For the first part, we examine the raw Hall effect data and normalize them between 0 and 1. Without any magnetic field from a reference magnet, the deviation of the values remains minimal. Given the low noise in the data, we can reasonably assume that when the deviation is below 0.03, no object is attached to the end-effector.

To detect a touch or movement, we can use the position detection from Section III-B. If the end-effector is stationary and the position changes or if the end-effector is in movement and the estimated position does not match, it suggests an interaction has occurred.

E. Simulation

Furthermore, the entire setup is simulated in Gazebo and ROS, enabling testing without hardware. Especially, the integration and development with VR or AR displays is improved.

IV. User Study

The haptic display is designed to provide feedback on-demand for users. To maintain the illusion, it is crucial to prevent users from reaching into empty space. To accomplish this, we need to determine the moment when users make contact with the object. Considering this duration and the table's velocity, we can calculate the available time for positioning the object, depending on the current and target positions. To evaluate the haptic display, we conducted a user study to answer the resulting research questions:

- R1 At what moment can a virtual object be presented to the user to ensure it arrives at the target position before the user reaches it?
- R2 Can our haptic display provide a satisfying user experience and usability?

A. Experiment Setup

We integrated a Meta Quest 2 with Unity (version 2021.3.27f1) into the environment to evaluate the table in virtual reality scenarios. To communicate with ROS and with the table, we used the ROS-TCP-Connector package provided by Unity. The user was seated on the long side of the table, facing 15 buttons, evenly distributed in three rows (see Figure 4). The participants were instructed to play a round of "Whac-A-Mole", where they had to press the button illuminated in red. During the experiment, the movement of the user's hands was tracked using the hand-tracking feature provided by the Oculus Integration SDK. As we suspect a difference in the duration of arm movements between imprecise and precise motions, we evaluated two conditions: in the first one, the users were asked to press the button with the flat hand, and in the second one, with the tip of the index fingers. Overall, the participants pressed the buttons 100 times, 50 in each condition. When the physical button is pressed, the virtual button is also animated accordingly. The virtual buttons cannot be manipulated otherwise and do not collide with the virtual hand.

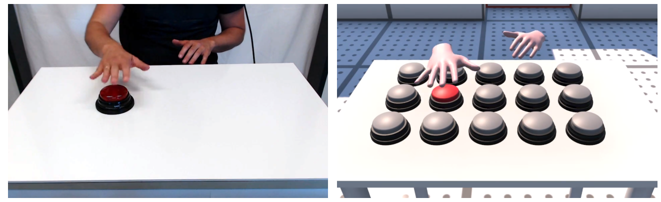

Fig. 4. Experiment setup in the real world on the left and virtual reality on the right.

TABLE I
AVERAGE DURATION OF MOVEMENT PHASES

	Tip	Flat	Overall
Latency phase	381 ms	389 ms	385 ms
Ballistic phase	440 ms	417 ms	429 ms
Correction phase	98 ms	42 ms	70 ms
Total	920 ms	848 ms	884 ms

B. Procedure

First, the participants got brief instructions about the experiment setup and tasks. Before the tasks began, they filled out the first questionnaire on a designated computer. In VR, the users had to register the position of the physical and virtual table by pointing at the front edges of the table, as no external tracking system was integrated. After that, they played two rounds of Whac-A-Mole and answered the remaining questionnaires. Overall, the experiment procedure took around 30 minutes, with approximately 10 minutes in VR.

C. Participants

Twelve participants volunteered for the study, consisting of 9 males, 2 females, and 1 person who preferred not to disclose their gender. The age distribution included 10 participants between 25 and 34 years, one between 35 and 44 years, and one between 55 and 64 years. The majority (11 out of 12) reported infrequent usage of VR (once a quarter or less), with only one participant using VR once a week. Only participants who did not state any visual impairments took part in the study.

D. Results

1) Hand Movement Duration: During the user study, we recorded 996 arm movements from our participants, 759

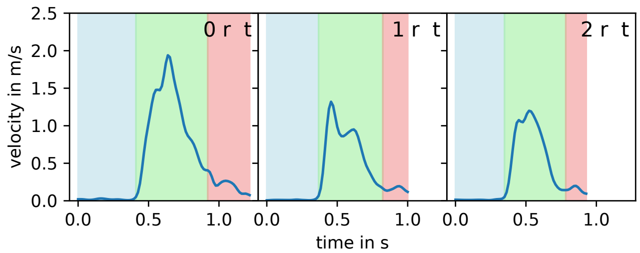

Fig. 5. Three exemplary graphs (0-2) of movement velocities with colored phases. Blue indicates the latency phase, green the ballistic, and red indicates the correction phase. All movements are right-handed (r), and the button is pressed with the fingertip (t).

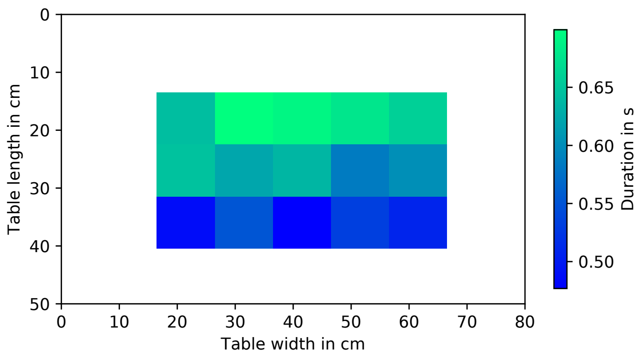

Fig. 6. The distribution of the minimum duration over the 15 button positions within the workspace. The colored region indicates the size of the workspace on the table.

were right-handed and 237 left-handed, 503 with fingertip presses, and 493 with the flat hand.

As established by Nieuwenhuizen et al. [20], goal-directed movements can be split into five phases: (i) a latency phase between the start of the task and start of the movement, (ii) an initiation phase with small motions before the ballistic phase, (iii) a ballistic phase, which is a faster movement to reach the target, (iv) a correction phase, i.e., a slower movement to correct unintended errors, and (v) a verification phase between the end of the motion and the end of the task. In Figure 5, the velocity curves of three sample movements are shown. Because the task ends immediately after pressing the button, we do not have a validation phase. However, we cannot discern an initiation phase in the data either.

Table I lists the average duration of each phase. Comparing *Tip* and *Flat* conditions, we observed a similarity in the latency phase, which corresponds to the reaction time and aligns with the expected outcomes. Regarding the ballistic and correction phase, the *Tip* motions take longer as they are more precise; for the ballistic phase 23 ms, and for the correction phase more than double as long, 56 ms. Looking at the minimum duration, for the latency phase, it was 210 ms, for the ballistic phase 111 ms, and for the correction phase 13 ms. The overall quickest movement took 477 ms which is the minimum time we have to bring the object to the target position to keep the illusion. Taking the most reliable speed of 66.6 cm/s into account, this results in a maximum distance of 31.7 cm to the target position before the virtual object can be displayed. Figure 6 visualizes the minimum movement duration for all 15 goal positions. The graphic has the size and proportion of the table from top view, the colored area is the workspace, and the user is positioned below the x-axis. As expected, the users need more time to reach goals further away. Furthermore, we can observe that the duration is slightly longer on the left-middle side, indicating that the right hand was used in this area, which is the dominant hand for most participants.

2) Simulator Sickness: To assess whether our system induced any form of simulator sickness, which might have a negative effect on the other measures, we used the *Simulator Sickness Questionnaire (SSQ)* [21]. The questionnaire was registered both before and after study participants were exposed to the VR environment, and values of the 16 assessed symptoms were subtracted (post–pre). The resulting differences were aggregated into the dimensions of *Nausea* ($M = -3.975, SD = 6.378$), *Oculomotor Disturbance* ($M = 0.000, SD = 9.142$), *Disorientation* ($M = 2.320, SD = 17.641$), and a *Total Simulator Sickness* score ($M = -0.935, SD = 5.319$). As can be seen, there is only a negligible increase in symptoms on the disorientation subscale, indicating that our system does not induce severe simulator sickness.

3) Presence: In the context of virtual environments, the sense of presence usually denotes the illusion of "being there" despite the certain knowledge that one is still in the real world [22]. Mismatches between visual stimuli (e.g., seeing a virtual button) and haptic feedback (e.g., touching a flat table instead of a real button) can diminish perceived presence and, in the worst case, cause a break in presence [23, 24].

A primary purpose of our haptic display is to reduce such mismatches, thus contributing to high presence values. We measured four aspects of presence using the 14 Likert items of the *Igroup Presence Questionnaire (IPQ)* [25]. Each aspect has a range from 0 to 6. The *Sense of Being There*, assessed through a single general item, yielded a high mean score of 4.833 ($SD = 1.115$). A similarly high score was achieved for *Spatial Presence*, i.e., the sense of being physically present in the virtual environment ($M = 4.617, SD = 0.936$). Slightly lower ratings were observed for *Involvement*, which covers the attention the study participants devote to the virtual environment ($M = 3.792, SD = 1.044$). The subjectively *Experienced Realism* yielded the lowest mean score ($M = 2.833, SD = 1.002$).

4) Perceived Workload: For assessing the workload involved in the Whac-A-Mole task, we used the raw *NASA-TLX* questionnaire [26]. Workload was measured on six 21-point Likert scales, each yielding a score between 0 and 100. Study participants reported low values for the *Mental Demand* ($M = 12.083, SD = 15.733$)

and *Frustration* level ($M = 7.917, SD = 7.217$). When rating how successful they were in accomplishing the assigned task, they indicated an almost perfect *Performance* ($M = 9.167, SD = 8.747$). Mean scores for *Physical Demand* ($M = 20.417, SD = 18.885$), *Temporal Demand* ($M = 29.583, SD = 25.977$), and required *Effort* to accomplish the level of performance ($M = 22.917, SD = 16.714$) were slightly higher, which can be directly attributed to the task of performing rapid hand movements during the study.

5) User Experience and Usability: With the short version of the *User Experience Questionnaire (UEQ-S)* [27], we measured our system's *Pragmatic Quality*, which covers interaction qualities related to the task, and *Hedonic Quality*, which describes aspects related to pleasure or fun while using the system. Values are measured on a 7-point Likert scale between -3 (e.g., "inefficient", "boring") and +3 (e.g., "efficient", "exciting"). Our system achieved excellent results (i.e., in the range of the 10 % best results from a benchmark data set [28]) for the *Pragmatic Quality* ($M = 1.917, SD = 0.779$), and good results (i.e., 10 % of results in the benchmark are better, 75 % worse [28]) for the *Hedonic Quality* ($M = 1.354, SD = 1.105$).

The overall usability, as measured by the *System Usability Score (SUS)* [29], yielded a mean value of 84.167 ($SD = 9.673$). This is equivalent to a grade of A, meaning it is in the top 10 % of SUS scores for 500 (non-VR) applications that were considered in a review by Sauro [30].

6) Haptic Experience: To measure the haptic experience of our system, we designed a custom questionnaire. The participants were asked to rate the extent to which the pressing behavior, shape, and position of the virtual button corresponded with the physical attributes using a 5-point Likert scale ranging from *Not at all* to *Very*. The results yielded mean scores of 4.417 ($SD = 0.900$) for pressing behavior, 4.833 ($SD = 0.389$) for shape, and 4.167 ($SD = 0.937$) for position.

V. Discussion

In response to the first research question (see Section IV), we can deduce that the minimum time available to position an object varies depending on its location in the workspace, ranging from 477 to 690 ms or 31.7 to 45.9 cm. Furthermore, with the two conditions, we have determined to have more time to position the object when the user performs a precise movement, as the correction phase is longer. This implies that we can cover, even with imprecise movements, more than half of the workspace.

With the questionnaires in the user study, we analyzed our system's user experience and usability and can answer the second research question. As our system achieved excellent results regarding Pragmatic Quality, good results for Hedonic Quality, and high outcomes for the haptic experience, we can conclude that the system provides a satisfactory user experience. Furthermore, we achieved a high usability score, which shows that the system can be used in VR scenarios. We attribute the medium score for experienced realism to the simplified virtual environment rather than the device itself, which achieved a good rating in haptic experience and likely did not contribute significantly to the lower score.

VI. Conclusion

In this work, we presented a newly designed Encountered-Type Haptic Display. The haptic display has an X-Y-Z-Yaw plotter-like architecture below the tabletop with four permanent magnets and the Hall sensors in the end-effector with a workspace of $47.2\,\mathrm{cm} \times 26\,\mathrm{cm}$. In a user study, we demonstrated that we can present objects on-demand over more than half of the table, while on the remaining portion, we can present them with a small delay. The overall experience and usability of the table are very positive, resulting from the questionnaires.

In future work, we will investigate to what degree we can improve the haptic experience by using hand redirection with the table [31, 32, 33]. Furthermore, we aim to explore the technical capabilities of the table further, such as collision detection and shape reconstruction, and reduce the friction to increase the maximum reliable speed.

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