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EGO-EXO: A Cooperative Manipulation Technique with Automatic Viewpoint Control

Leonardo Pavanatto Soares
School of Technology
PUCRS
Porto Alegre, Brazil
leonardo.pavanatto@acad.pucrs.br

Regis Kopper
Department of Mechanical Engineering and Materials Science
Duke University
Durham, USA
regis.kopper@duke.edu

Márcio Sarroglia Pinho
School of Technology
PUCRS
Porto Alegre, Brazil
marcio.pinho@pucrs.br

***Abstract*—Cooperative manipulation techniques allow multiple users to interact with an object together at the same time. This kind of collaboration allow users to solve complex tasks that would be difficult for a single user to perform. The EGO-EXO technique proposed in this paper places two collaborating users in asymmetric viewpoint positions. It was developed from the premise that simultaneous control over navigation and manipulation by the user can increase the interaction complexity. Our technique allows one of the users to follow the object being manipulated automatically while the other stays in a fixed position farther away. Our technique separates the degrees of freedom between the two users, matching the degrees to the most suitable viewpoints. Each user interacts with objects using complimentary manipulation techniques, which were chosen based on which degrees they control. EGO-EXO is implemented and evaluated through a user study to test how well it performs when compared to a similar technique when both user viewpoints are fixed.**

***Index Terms*—Cooperative manipulation, 3d manipulation, virtual reality**

I. Introduction

A Collaborative Virtual Environment (CVE) is defined as an immersive virtual space where multiple users can interact with each other and the environment while trying to achieve a common goal. Users usually perform their interactions with the environment individually, having full authority over the object each of them is applying manipulations. However, some CVEs allow their users to interact with the same object concurrently by combining their individual actions into a single manipulation. This combination between both inputs is defined by a cooperative manipulation technique [12].

Several techniques for cooperative manipulation have been proposed in the literature in the past two decades [1], [4]–[6], [9], [12]–[14]. Derived from techniques developed for single user Virtual Environments (VE), these cooperative manipulation techniques aim to take advantage of multiple users working together to allow the solution of complex tasks that would be difficult for a single user to perform [12].

According to Bowman [3], most interaction tasks performed by users in 3D environments can be divided into three universal categories: navigation, responsible for the movement of the user's viewpoint; selection/manipulation, the actions of choosing an object and applying translations or rotations; and system control, responsible for applying changes to the state of the system. In most VE implementations these categories are treated separately, requiring the user to control navigation and object manipulation at the same time. This could result in an elevated cognitive load and deteriorate performance, especially when the navigation task requires the user to find their way through an environment [8].

Combining different types of selection and manipulation techniques is an important strategy when designing cooperative manipulation techniques [12]. These techniques can be split into two categories: the ones that try to act resembling the real-world, related to an isomorphic view; or the ones based on "magic", related to a non-isomorphic view. The first is used to build a faithful, more natural, representation of the physical world, while the last is mapped and tailored specifically to 3D environments [3], [8].

Mine [10] argues that there are two types of selection techniques: local and at-a-distance. Local techniques allow the user to grab an object that is within its reach, while at-a-distance techniques allow the user to select an object that can't be reached. LaViola et. al [8] goes further, and suggests a metaphor-based taxonomy with six categories for 3D manipulation: grasping, similar to the local techniques; pointing, similar to the at-a-distance techniques; interacting with a surface, mainly used for touch screen displays, where dragging or rotating are performed once the users touches the screen and moves their finger; indirectly manipulating objects, where the user does not interact directly with the object (no need to navigate to the object's position); bimanual interactions, where both hands are used to perform the manipulation; and combining metaphors to create hybrid techniques.

Along with complimentary manipulation techniques, the viewpoint position of the user is also a key point to make a cooperative manipulation easier and more efficient [12]. This happens because each user can be placed at a position where they can see information about the manipulation or the environment that their partner cannot. Focus + context techniques define ways on how to blend detailed information with the context to which it is inserted [7]. In the case where we have two users collaborating, this concept of focus vs context can be separated and the users' viewpoints can be

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defined to provide different levels of details, with one user focused on the details of the manipulation, while the other on how the manipulation is inserted in the environment context.

This work presents a manipulation technique based on the placement of two users in asymmetric viewpoint positions, as proposed by Soares *et al.* [14] and Le Chénéchal *et al.* [9] for the IEEE 3DUI 2016 Contest. The EGO-EXO technique uses two well defined viewpoints relative to the object being manipulated: egocentric and exocentric. The egocentric viewpoint automatically positions one user near the object being manipulated, while the exocentric viewpoint lets the user positions themself at a fixed position before starting the manipulation. As in the work of Pinho [12] it also applies the separation of Degrees of Freedom (DOF) technique between the two users and the use of different manipulation techniques for each one.

A user study was conducted to analyze whether the proposed technique performed better than a baseline technique where both users have an exocentric viewpoint. We hypothesize that by having the egocentric user attached to the object from a close distance and free of navigation control, will yield a better performance and reduced number of collisions.

This paper is organized as follow: first we explore some related work; then the EGO-EXO technique is explained in details, including its viewpoints, selection and manipulation techniques, concepts on navigation, and the feedback in CVEs; the user study is described, including the apparatus used, the participants, the tasks to be solved and procedure; the results are present, considering information collected on runtime and a questionnaire; a discussion is done based on the results; finally, some conclusions are presented along with future work.

II. Related Work

There are some classical approaches [3] on how to handle both selection and manipulation that can be used in the proposed technique:

- **virtual hand**: a 3D cursor, most times shaped like a human hand, moves according to a hand tracker; Regarding Mine's classification [10], it is considered a local selection and manipulation technique.
- **ray-casting**: a virtual ray emanates from the virtual hand and is used to select and manipulate objects by pointing to them.It is considered an at-a-distance selection and manipulation technique, because the virtual ray can grab objects at any distance.
- and **go-go technique**: based on the virtual hand, but the mapping becomes nonlinear when the user extends the hand farther than a threshold distance. It is a hybrid between local and at-a-distance selection techniques.

Another issue that should be considered is the way that the users' actions are combined to allow the cooperation. The following techniques define how to combine interaction techniques for multiple users [9]:

- the **average technique**: both users can apply translations and rotations to the object, while the resulting transformation matrix is formed by the average of each user's operations.
- the **separation of degrees of freedom**: where the 6 degrees of freedom (DOF) (translations in x, y and z axis, along with yaw, pitch and rolling rotations) are separated between the users [12].
- and based on the **point it was selected**, where each user will grab a crushing point of the object, and the operations will be applied relative to the crushing point position. It is similar to real life, when two people are moving a big object by grabbing on opposite sides. One implementation of this technique is the Skewer 3D [5].

Le Chénéchal *et al.* [9] proposed a technique similar to EGO-EXO. One user would be considered a giant, from a viewpoint above the environment, and the other an ant, from a viewpoint inside the manipulated object. It used different types of input devices and manipulation techniques, along with separation of degrees of freedom between users.

The EGO-EXO technique, however, restrains the interaction techniques and input devices to focus on the evaluation of the viewpoints. Based on these high level constraints, EGO-EXO aims to take advantage of multiple manipulation techniques and different viewpoint positions to provide an efficient method for cooperation.

Network performance should also be considered when developing this collaborative environment. As discusses by Park [11], high latency can have an impact on users' coordination, while high jitter can reduce the ability to predict actions. This could led to users seeing different scenes, forcing them to wait for synchronization or get inconsistent results.

III. EGO-EXO Technique

We proposed EGO-EXO, a cooperative object manipulation technique specifically designed for manipulation tasks which require high amplitude translation coupled with precise rotation of the object. It aims to take advantage of two users in asymmetric viewpoint positions (egocentric and exocentric viewpoints) along with a specific control over degrees of freedom for each viewpoint user.

A. Viewpoints

The egocentric viewpoint (EGO - Fig. 1) positions the user at the scale and in near proximity of the manipulated object. It allows the user to see the immediate surroundings of the controlled object, resulting in a better precision for rotation operations using a virtual hand technique. The EGO user position follows the manipulated object automatically, as it gets translated by the EXO user.

The exocentric viewpoint (EXO - Fig. 2) has the user positioned at room scale and at a distance from the object to be manipulated. It allows the user to have an overview of the object and the environment surrounding it, resulting in better performance for high amplitude translations using a ray-casting with reeling technique [2]. The EXO user places themself using some navigation technique at a suitable position before the start of manipulation, at which point navigation

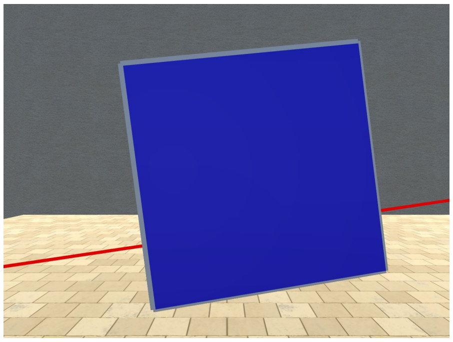

Fig. 1. Egocentric viewpoint. The ray from the EXO user can be seen passing throught the object.

for this user is disabled, so they can focus entirely on the manipulation task.

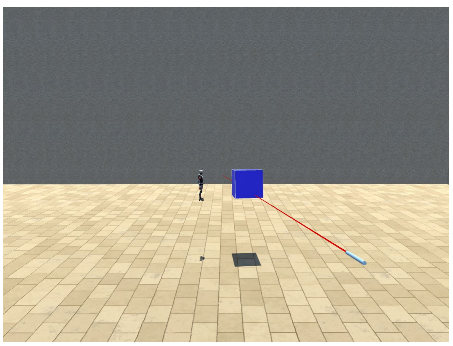

Fig. 2. Exocentric viewpoint. An avatar of the EGO user can be seen left to the object.

B. Selection and Manipulation

The technique proposes the use of a ray-casting technique for selection. Both users can choose which object they would like to select individually. The ray-casting is used for selection because it allows the users to select objects that are not close to them. As an alternative, the selection could also be implemented using the go-go technique and its derived approaches.

Once the object is selected, the user can apply manipulation techniques to interact with it. The EGO user utilizes a virtual hand technique to apply rotations to the object. Since the user is closer to the object and translation information is disregarded, it is easier and more efficient to use a local manipulation technique, such as a virtual hand, than a ray-casting, which limits some rotation axis. The EXO user utilizes uses a ray-casting with reeling to apply translations to the object. The ray-casting technique allows the users to translate the object quickly, while the reeling functionality allow the translation in depth of the object. Alternatively, a go-go technique could also have been used for the EXO user.

By combining two users with specific controls over the manipulation of an object, some issues are addressed. It is difficult to rotate the object around its own axis using ray-casting, but the EGO user can precisely rotate around all axes using a virtual hand technique. Conversely, it is difficult to translate the object long distances using a virtual hand, but since the translation is done by the EXO user through ray-casting with reeling, high amplitude translations can be easily performed.

C. Navigation

A navigation technique needs to be used along the EGO-EXO technique to allow the users to travel in the environment before they start the manipulation. The EGO user needs to position themself in order to select the object from the right orientation, since this determines from which side of the object they will be attached to. The EXO user needs to position themself before selecting the object, because their viewpoint position becomes fixed at that position after that.

In our implementation of the EGO-EXO technique, we used a steering navigation technique, allowing the user to translate in the direction of the ray when pressing a button, along with two buttons for right and left rotation. However, other techniques could be used without interfering with the proposed technique.

D. Feedback

A feedback component is responsible for making sure that the users get a visual feedback of their actions in the environment to maintain a higher level of awareness. This can be achieved by using changing colors, shapes and position of objects as users interact with them.

In VEs, this kind of feedback aims to warn the user of their own actions [12]. Additionally, in CVEs, there is a necessity of coordination between the users. In this case, we can divide these feedbacks into two categories: feedback of the user's own actions; and feedback of the other user's actions.

As feedback of the user's own actions, a change can be made in the colors of the cube depending on the state of collision, and in the colors of the ray depending on the state of the ray-casting (if the object can be select, if it is selected). As feedback of the other user's actions, a change can be made in the colors of the object when it is selected by the users (Fig. 3). In EGO-EXO, the object faces change color when the EGO user selects it, while the edges change color when the EXO user selects it. This way both users can know if the other has selected it.

IV. Evaluation

We performed an evaluation to compare EGO-EXO to an exocentric-only (EXO-EXO) manipulation technique, where both users are able to change their viewpoint positions before selecting the object. In the EXO-EXO technique, the division of degrees of freedom, and the manipulation techniques used by each user was maintained. Our objective with EGO-EXO is to analyze the asymmetric viewpoints where automatic travel is performed by the EGO user, thus we compared it against a technique where no user follows the object.

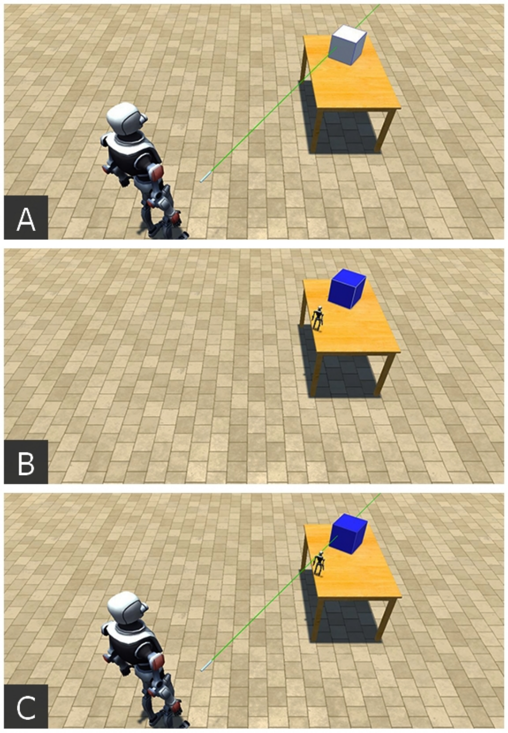

Fig. 3. Feedback of other user's action. Object not selected (a); object selected by egocentric (b); object selected by both (c).

A. Apparatus

The application used consists of a Unity developed software that implements the proposed technique. It runs in three computers at the same time, with one being a server and two as clients. The communication used UDP/IP, to reduce lantency, and the simulation of the environment was done only in the server, to guarantee that all instances were running the same scenario.

Oculus Rift DK2 head-mounted displays, with $960 \times 1080px$ resolution per eye, 75Hz refresh rate and 100 degrees diagonal field of view, were used by both participants. Tracking was provided by a Polhemus Fastrak magnetic device, which has guaranteed accuracy of 0.08cm RMS for position and 0.15 degrees RMS for rotation within 76cm, 4ms latency and 60Hz refresh cycle. The receiver was attached to a mouse, allowing the user to use the same hand for tracking and pressing buttons.

B. Participants

The evaluation was conducted in pairs. 20 participants (3 females), with age ranging 18-47 years (median age 23 years). 12 participants were undergraduate students, 6 were graduate students 2 were professionals. 11 participants had experienced VR before, but only 4 had used a Head-Worn Display (HWD) prior to this test, while 15 participants had used some sort of tracking device.

C. Tasks

Four tasks were proposed (Fig. 4). In each of them, the participants needed to move objects through tunnels while avoiding collisions.

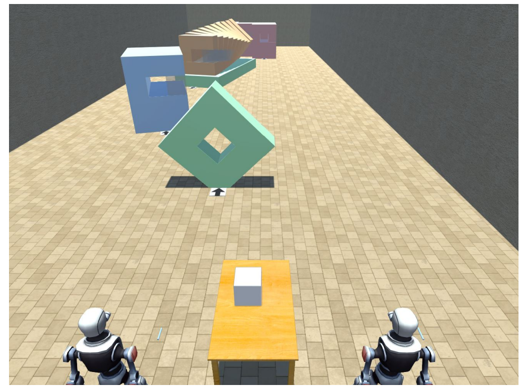

Fig. 4. Tasks scene overview. Avatar representation of participants (bottom), the object to be manipulated (cube over the table), and the four tasks (top).

In the first task (Fig. 5, left), the participants had to move an object from the start position through a green obstacle, while applying a rotation of 45 degrees in the roll (Z) axis. This task aimed to be simple, so participants could learn the control of the input devices and the technique. In the second task (Fig. 5, right), the participants had to move the object through a blue tunnel, while applying a rotation of -15 degrees in the yaw (Y) axis and returning to 0 degrees in the roll (Z) axis. This task aimed to be harder than the first one, while evaluating the combination of translation and rotation. One of the sides of the tunnel was semi-transparent to allow the exocentric user to view the object.

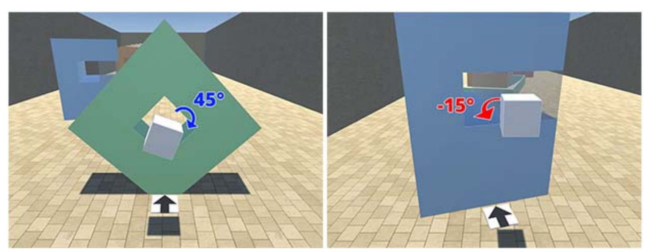

Fig. 5. First task (left), second task (right), and their rotation angles.

In the third task (Fig. 6, left), the participants had to move an object through a tunnel, while applying a rotation of 15 degrees in the yaw axis. At each segment of the tunnel they needed to add an extra 5 degrees in the roll axis to avoid collision. This task is the only one in which both participants must apply their operations at the same time to solve it. In the fourth task (Fig. 6, left), the participants had to move an object through a red S-shaped tunnel, without the need to rotate the object. In this task, the participants had to pay special attention to the end of each section, to avoid collision. Although there was no need for rotation during the task, the egocentric user could help the exocentric with verbal information due to their advantage viewpoint.

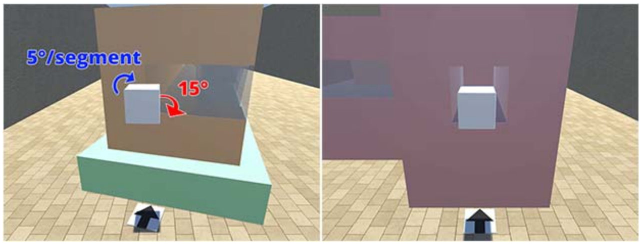

Fig. 6. Third task (left), fourth task (right), and their rotation angles.

D. Procedure

Participants had to sign a consent form, which briefly explained the study, and guaranteed their rights during the evaluation. These rights included anonymity of the generated data, the access to the results of the research, the possibility of stopping the test at any time if the participant felt embarrassed, and the right to disagree with any of the previous terms.

They were given an explanation about the study. It was explained how a CVE works, how the usage of the hand tracker and HWD, how the degrees of freedom between them would be separated, and how many tasks they would need to perform. Participants were encouraged to keep communicating with each other during the experiment to coordinate how the manipulation would work.

Each set of four tasks was performed under a specific block, in the following order: EXO-EXO; EGO-EXO; EGO-EXO with roles reversed; EXO-EXO with roles reversed. This within-subjects design and its ordering were defined to obtain more data from each pair, while minimizing a potential learning factor.

The first block (EXO-EXO) was used by the participants to learn how to use the devices and manipulation techniques. The second block (EGO-EXO) was the first one to obtain useful data from a set of metrics. The participants were familiar with the environment due to the first block, and were able to complete the tasks with the new technique. The third block (EGO-EXO with roles reverse) also evaluated the technique, but the viewpoints, manipulation techniques and degrees of freedom between the participants would be different than their previous experiences, minimizing a learning factor. As this work aims to evaluate the efficiency of the EGO-EXO technique, the technique that was used for comparison (EXO-EXO with roles reverse) was tested on the last block one, after participants had trained the most.

There are some reasons for using this unusual experiment design instead of counterbalancing between subjects: participants were able to try all the tasks before starting the relevant data collection, in this way they would correctly understand what they had to do in each task, while also training the usage of the devices; the effects of the egocentric user were isolated on the second and third blocks, since in both cases the user performing the exocentric viewpoint had already used it before; finally, the last block evaluated the EXO-EXO, since this is the baseline we are comparing against, and participants would have performed this viewpoint once for each manipulation technique, which guarantees that no learning factor is involved.

During the first block, before the participants started solving the tasks, it was explained to them how the input devices should be used to perform the navigation and the selection and manipulation techniques. During this first block, an explanation was given to each task, to help the participants understand what they should do.

After the tests were completed, each participant completed a post-experiment questionnaire with background information and specific questions about their experience using the system. Among the questions, we ought to find out if one of the viewpoints was preferred over the other, how easy was the overall manipulation, how easy it was the coordination between the participants, and if they felt discomfort while using the egocentric viewpoint.

E. Methods

The techniques were evaluated by two methods: obtaining metrics from each pair's simulation, and then finding the ratio between the amount of time in which the object they were manipulating was in a collision state, and the amount of time they took to complete the task; and a post-experiment questionnaire, were participants were asked about their previous familiarity with elements of the test, background questions, such as age and scholarity, and their evaluation on the techniques they used.

V. Results

A. Time and Collision

The first step was to evaluated the results for each block of tasks. The average of each of the metrics was obtained from each pair of participants, which can be seen in Fig. 7.

As expected, the first block (EXO-EXO) took more time than the others, and the object stayed in collision with the obstacles for more time. The second block (EGO-EXO) had a reduction in the task completion time and the amount of time in which the object stayed in collision. In the third block (EGO-EXO with roles reversed) participants took more time to complete the tasks while colliding more. This was expected due to a learning factor, since when the participants changed their viewpoints, DOF controls and manipulation techniques. The fourth block (EXO-EXO with roles reversed) presented the best overall results, with the best time in collision per time to complete task ratio.

To analyze the techniques instead of the block of tasks, each pair metrics was converted into two entries of data: one with second block (EGO-EXO) and fourth block (EXO-EXO with roles reversed) data, and another with third block (EGO-EXO with roles reversed) and fourth block (EXO-EXO with roles reversed) data. A ratio of amount of time in collision per time

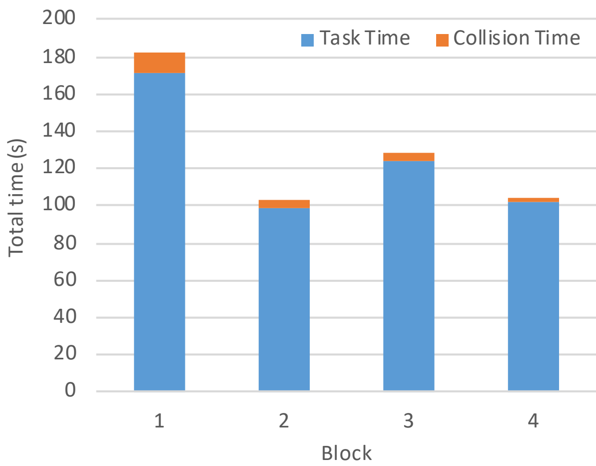

Fig. 7. Average result for each block (in seconds), considering total time to complete the tasks, and total time in collision.

to complete the task was made for each entry in each task, including the sum of all tasks.

A single factor ANOVA was performed between the ratios found for each technique in each of the tasks. These results can be seen of Fig. 8. It was found no statistically relevant difference between the techniques ($p = .28$).

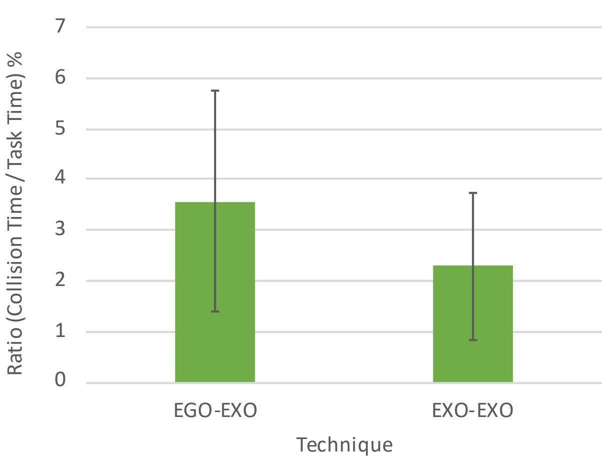

Fig. 8. Average ratio between collision time and task time for each technique.

B. Questionnaire

Beyond the metrics data obtained during the simulation, participants were also asked to answer a few questions in a post-experiment questionnaire. When asked about whether they felt more discomfort using the egocentric viewpoint than the exocentric, 45% (9 participants) said they did. However, the questionnaire also showed that the participants generally preferred the EGO-EXO technique. 15 participants (75%), considered the EGO viewpoint better than the EXO viewpoint when applying rotation operations. This indicates that participants preferred to stay close to the object, being able to clearly observe their actions.

VI. Discussion

The results show that the EGO-EXO technique did not perform better than the baseline technique in both total time and the ratio collision time per task time. This indicates that our hypothesis is incorrect, but a few factors should be discussed.

The user with the exocentric viewpoint was able to place themself at any position, even the same as the egocentric user would be. Since the egocentric position seemed the most appropriate for rotation, exocentric users also chose a position similar to it, since they were also performing the same operation. Aligning this with the result that many participants had more discomfort when using the egocentric viewpoint leads to a situation where the exocentric viewpoint was a good viewpoint, but did not have the issues of discomfort and cybersickness of the egocentric viewpoint.

Moreover, the low rate of collisions for both techniques indicate that the tasks were easy (bellow 4%). Perhaps the tasks were too easy to measure any difference, and with more complex tasks the performance would be different.

VII. Conclusion and Future Work

This work proposed a cooperative manipulation technique by combining the concepts of separation of degrees of freedom and asymmetric viewpoint positions. The technique divided the degrees of freedom between an egocentric user, that uses a virtual hand to apply rotations to the selected object, and an exocentric user, that uses a ray-casting with reeling to apply translations to the selected objects.

A prototype was developed and evaluated through a user study. The study aimed to compare the EGO-EXO technique and a technique with both users positioned in an exocentric viewpoint. In pairs, participants had to solve 4 tasks that were designed to evaluate aspects of the collaboration. A within subjects design was used, and the ordering designed to minimize a learning factor.

The results of the evaluation showed that most participants preferred the EGO-EXO technique, although most of them also felt discomfort when using the egocentric viewpoint. Results showed that the proposed technique did not perform better than the baseline under the study conditions.

For future work, there are a couple of paths that can be followed. A replica of this study using tasks with increased complexity and higher number of participants might lead to better results. Another approach would be to eliminate the navigation task, and perform an experiment where the exocentric users have fixed positions, isolating a factor that could have influenced the results. Evaluating the opposite scenario, where egocentric users can apply translations and exocentric users can apply rotations instead of considering the current combination the optimal. And finally, another study with all the combinations of EGO-EXO, EXO-EXO, and EGO-EGO, could lead to a better understanding of the problem.

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