Virtual Hand-Button Interaction in a Generic Virtual Reality Flight Simulator

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Abstract—**Flight simulators with a physical mock-up are dependent on the aircraft type and have high costs. In order to overcome high cost issues, a generic virtual reality flight simulator is designed. Virtual buttons are used without a physical mock-up to make the virtual reality flight simulator independent of the aircraft type. The classic virtual hand metaphor is employed to interact with the virtual objects. This paper examines the virtual hand-button interaction in the generic virtual reality flight simulator where no haptic feed-back is provided. The effect of the collision volume of a virtual button during the virtual hand-button interaction is determined. It is concluded that a change in the collision volume within aircraft design limits, does not have a significant impact on the interaction. We also investigate different virtual hand avatars. We find that the accuracy of hand-button interaction depends on the hand avatar rather than the collision volume. Representing a smaller part of the hand avatar results in less efficient interaction. This shows the size and shape of hand avatars plays a major role in the virtual reality simulator design. This finding contributes to the various virtual reality applications which exploit the virtual hand metaphor.**

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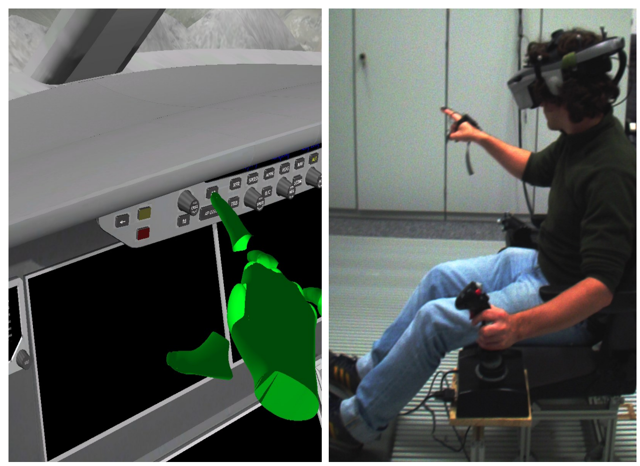
1. Introduction

Virtual reality flight simulators are created for various purposes, such as pilot training and virtual prototyping. To reduce costs, these flight simulators are required to be adaptable to different types of aircraft. Interaction with purely virtual objects is needed for adaptability. However, this reduces the naturalness of the interaction since there is no sense of touch and no force feed-back. Therefore, simple tasks, such as switching a virtual button on/off or pushing a virtual slider on a cockpit panel can be challenging.

Buttons are commonly used in aircraft cockpits. The interaction with buttons in the virtual reality flight simulators should be intuitive and efficient for pilot training. Moreover, aircraft designers need realistic hand-button interaction for testing aircraft setups in the Virtual Reality Flight Simulators (VRFS). One distinct factor that plays a role during the interaction is the button size. Several studies have been performed related to the button size on touch screen pads [1]. To our knowledge, the effect of the button size in an industrial virtual reality application is not examined since the button size generally depends on the industrial design and cannot be changed. However, collision volume of a button can be easily modified instead of visual volume. Therefore, we investigate the effect of the button's collision volume on the hand-button interaction while the button size visually does not change.



(a) (b)

Figure 1. Virtual hand-button interaction in the VRFS, (a) The view of the user, (b) The mock-up and hardware. There is no physical mock-up for the virtual buttons.

The virtual hand representation can play a major role during the virtual hand-button interaction (Figure 1). It is represented by a hand avatar or a cursor. The hand avatars are usually categorized as *self-avatar* or *no-self avatar* [2]. The term *self-avatar* refers to the visual appearance of the users' hand. In our VRFS, we employ a scanned male hand as a hand avatar. Our hand avatar is a *no-self avatar* in this case. It is not realistic in comparison with those commercially available. However, it is expected to perform as well as the realistic hand avatars according to [2]. Although we observe a faithful experience with our hand avatar, it makes users unable to see virtual buttons during the interaction due to the occlusion of virtual objects by hands. This might have a negative effect on the user performance. Because of the complex structure of the human hand, the designers of VR (Virtual Reality) applications also prefer to work with simplistic hand avatars. Therefore, the use of a partly visualized or a simplistic hand avatar might have an advantage over a detailed human hand avatar.

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The topic of aimed movements in 3D space has been studied earlier [3]. The practical issues related to the use of virtual reality simulations for the evaluation of operating panels are well known. Moegring and Froehlich demonstrated the task performance of natural interaction metaphors in a system where a Head Mounted Display (HMD) and Computer Assisted Virtual Environment (CAVE) were employed [4]. Their research includes that the use of a HMD with a virtual hand representation can be more beneficial than the use of a CAVE without employing a virtual hand for the manipulation of fine-grained and small objects. Pusch et. al presented the effects of hand feed-back fidelity on near space pointing performance in a HMD-based application [5]. They focus on the realism of the hand avatars. Their results conclude that a more realistic hand avatar provides faithful experience but it does not have a strong impact on the task performance. However, their research does not describe the relation between the task performance and represented volume of hand avatars.

The occlusion of virtual objects by hands can make tasks more difficult. This problem is addressed by [6] and solutions, such as the usage of a semi-transparent hand or a 3D cursor [7] are suggested. Buchmann et. al conclude that the transparent virtual hand has some drawbacks at higher transparency levels, such as conflicting depth cues and feeling of reduced control [8]. On the other hand, the previous work does not include a partly visualized hand avatar as a solution to this problem.

This paper is an extended version of our publication on our generic virtual reality flight simulator [9]. Previously, we introduced the architecture of the VRFS. In this paper, we make a comprehensive assessment of the virtual hand-button interaction and we describe our method to interact with the virtual buttons in detail and examine virtual buttons and alternative hand avatars.

The main contributions of this paper are:

- We explain a virtual hand-button interaction technique and its implementation in the generic VRFS.
- We investigate the use of the hand avatars with different granularities where virtual objects are frequently concealed by virtual hands.
- We show that representing a smaller part of the hand avatar results in less efficient interaction. Hence, occlusion of virtual buttons by a virtual hand does not have a strong effect on the interaction.
- We demonstrate that the collision volume of a button does not have an impact on the virtual hand-button interaction in design limits of an aircraft cockpit.

This paper starts with the overview of the VRFS. We introduce the central components of the system. In Section 3, we describe the virtual hand-button interaction in the simulator. We explain how it is implemented. The information about the selected hand avatars is also given in this section. In Section 4, we present user studies with regard to the effect of the virtual buttons' collision volume and different hand representations with granularities. In Section 5, we discuss the results of the user studies. Finally, we give the conclusions of our findings in Section 6.

2. The Generic Virtual Reality Flight Simulator

In this section, we give an overview of our VRFS system. For more details about the architecture we refer to [9].

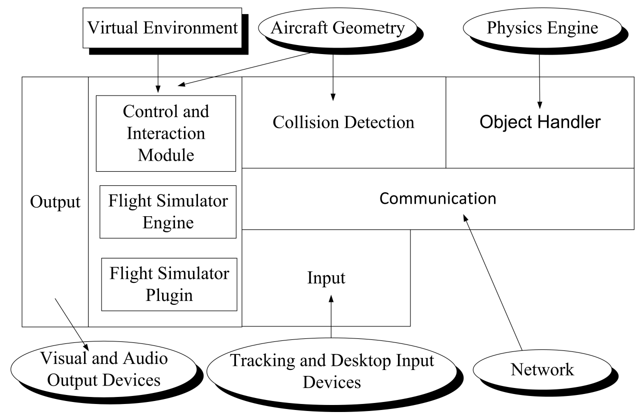


Figure 2. The basic modules of the generic VRFS. The communication module is the most central module.

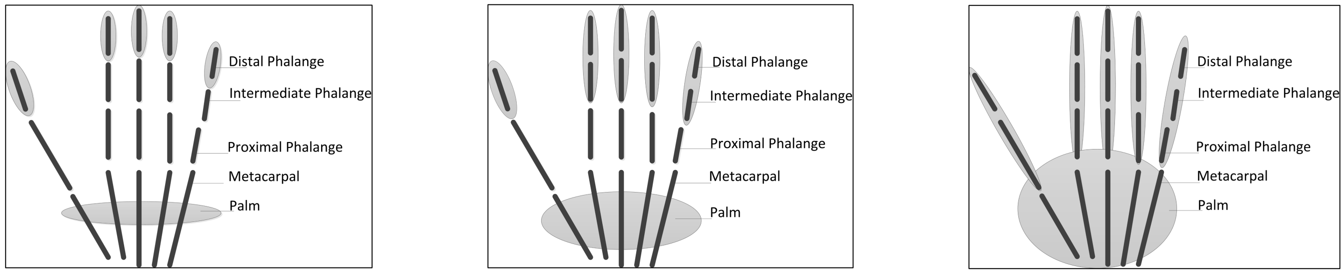
To increase the adaptability and extensibility of the VRFS, we followed a modular approach during the design of the software components. The central software components are a virtual environment module, a communication module, an object handler module, and a collision detection module (Figure 2). The modules can be replaced and additional modules can be integrated to the virtual reality flight simulator on demand.

Different desktop flight simulators, such as X-Plane or FlightGear or in-house-developed virtual environments can be integrated into the VRFS. As a virtual environment, we have chosen X-Plane 9. This is a desktop flight simulator environment which is currently in use of flight simulators for pilot training and it also has Federal Aviation Administration (FAA) certification with validated hardware. It provides a realistic flight environment to the VRFS. The object handler module is responsible for the human-computer interaction including the interaction with the virtual buttons. The collision detection module is integrated into the object handler module. The communication module exchanges data among the software components. Stereoscopic views are provided to give more feeling of presence using the virtual environment module.

An optical tracking system (ART Optical Tracking System) for finger and head tracking, a joystick, a throttle and pedals with other additional desktop input devices, such as a keyboard and a mouse are used as input devices. A HMD (Nvisor SX60) and stereo headphones are employed as output devices.

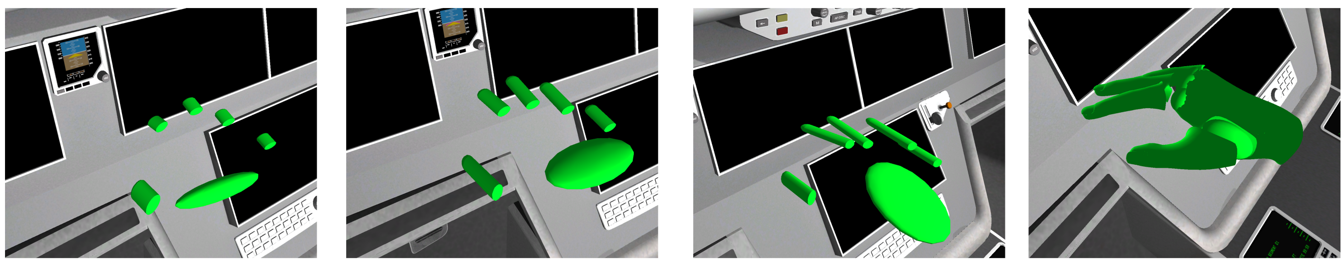
A seating buck is provided to align the virtual environment and the real world. Actually, the seating buck is a simplified mock-up with low cost constraints. They have already been in use by automotive industry [10]. Our seating buck contains a cockpit seat which is surrounded by the basic flight hardware, such as a joystick and pedals. The seating buck is also tracked for the co-location of the virtual and real objects.

The frame rate of the virtual environment is faster than 25 fps. The optical tracking system reduces the tracking-lags since the tracking targets are detected by 6 cameras. Hence, the effects of latency on user performance would be minimal.



(a) (b) (c)

Figure 3. The abstract hand avatars, (a) Hand avatar X, (b) Hand avatar Y, (c) Hand avatar Z. The gray area shows the represented volume of the hand.



(a) (b) (c) (d)

Figure 4. The hand avatars in the virtual environment of the VRFS, (a) Hand avatar X, (b) Hand avatar Y, (c) Hand avatar Z, (d) Detailed hand avatar. The hand avatars are shaded. There is no texture on the hand avatars.

3. VIRTUAL HAND-BUTTON INTERACTION

In this section, we explain the interaction method and how it is implemented in the VRFS. Subsequently, we describe the hand avatars that are also used during the user studies.

Description of the Interaction Method

Manipulation and selection are fundamental tasks for both virtual and physical environments. The human hand is a remarkable device that allows us to manipulate objects. Therefore, various interaction metaphors have been suggested with regard to selection and manipulation of the objects by the human hand in the virtual environments. The classical virtual hand technique is a common interaction metaphor in the VR applications. The VRFS also employs this interaction metaphor. It can be used for both selection and manipulation of virtual objects. In this paper, we will focus on the selection since it is chosen for the virtual hand-button interaction.

Bownman et al. classifies the selection technique by task composition into three categories [11]:

- Indication of objects: In the VRFS, indication of objects is achieved by touching. A button functions when it collides with the virtual hand.

- Confirmation of selection by the user: In the VRFS, additional confirmation is not provided.

- Feed-back: In the VRFS, feed-back is provided visually by changing the color of the virtual hand as haptic feed-back can not be provided. When the virtual hand is in contact with a virtual object, the color of the hand turns to red. The virtual hand is green for the rest of the situations. Also, the buttons are lightened when they function.

In the VRFS, the virtual hand technique allows users to directly select objects with their hands. The position and orientation of the finger tracking device is mapped to the virtual hand. Therefore, users can easily move their hands to touch virtual aircraft objects.

Implementation of the Interaction Method

The interaction method is mainly implemented in the object handler module which controls the interactions in the virtual environment exploiting an event based approach [12]. This approach is based on inputs, events, actions, and objects. Inputs can be considered the interface to the real world. The input to events has always one of two states: true or false. Hence, events can be used as starting and stopping criteria for the actions. In this case, they can be boolean expressions that trigger the actions. The actions should be considered as independent functions that affect the virtual objects in the virtual environment. In other words, they bring a virtual environment to life. All the object properties are specified through actions.

Algorithm 1 Button events in the object handler module

for ID=0 To $TotalNumberOfButtons$ **do**
    ButtonEvents[ID] $\leftarrow$ False
end for
loop ▷ Each Frame
    for ID=0 To $TotalNumberOfButtons$ **do**
        if A Finger Collides with Button[ID] **then**
            ButtonEvents[ID] $\leftarrow$ True
        else
            ButtonEvents[ID] $\leftarrow$ False
        end if
    end for
    SendButtonArray(ButtonEvents) ▷ Sends to the virtual environment module via the communication module
end loop

In the VRFS, inputs are mostly the collision data, events are an array of boolean variables and actions are the commands. The collision data changes the state of events ('true' or 'false') in the object handler module. In the beginning of the simulation, the array of the events is initialized to "false" (Algorithm 1). The events are sent to the virtual environment module via the communication module each frame. These events enable the commands when their state is true. The commands are implemented in virtual environment module. The commands change the state of the objects in the aircraft. They can start or stop animations. For instance, when a user touches the Auto Pilot (AP) button in the aircraft, first, the user's virtual finger collides with the virtual AP button geometry. This creates the collision data. The AP event (a boolean variable) becomes 'true' in the array of events while the other boolean variables are 'false'. Then, this array is sent to the virtual environment module via the communication module. In the virtual environment, the AP event enables the AP command and the virtual AP button is turned on and the light of the virtual AP button is lit. If a finger collides with the same button again, the data flow will be in the same direction but the boolean expression will be switched back in the virtual environment module and the button will be turned off.

In the VRFS, the inputs of the hand-button interaction depend on the collision volumes of the virtual hand and buttons. These are assigned in the object handler module and they can be modified. We only use the distal phalange of fingers as a collision volume to interact with the virtual buttons in the VRFS since this corresponds to natural interaction in the real world. We do not press buttons using palm of our hands, for example. The usage of a sophisticated hand avatar as a collision volume may also decrease the performance of the system since the collision of the hand avatar with each cockpit object should be computed on each frame. As result, a sphere located at the tip of fingers as a bounding volume of distal phalanx or the mesh of distal phalanx would be sufficient for collision detection where the virtual hand-button interaction happens.

Hand Avatars

We have created a detailed hand avatar in the beginning for the virtual hand-button interaction. The detailed hand avatar is a scanned hand geometry of a male hand which almost had average (50 percentile) male hand size. To investigate the effect of the different hand avatars, we have also created abstract hand avatars with different granularities (Figure 3). These avatars are also created using 50 percentile human hand measurement. These hand geometries are modelled by using the primitive types of geometries, such as ellipsoid (Figure 4). The primitive hand avatars are explained below:

• *Abstract Avatar X* only consists of the hand geometry where distal phalange is located. The palm of the hand is represented by an ellipsoid-like shape. The size of the palm is same as the size of 50 percentile male human hand palm but the length of the ellipsoid is proportional to the distal phalange length.

• *Abstract Avatar Y* consists of the hand geometry of the distal and intermediate phalange. The palm of the hand is represented by an ellipsoid-like shape. The size of the ellipsoid-like shape is as same as the hand avatar X but the length of the palm is proportional to the sum of the distal phalange and intermediate phalange length. Its volume is almost two times bigger than the small hand avatar.

• *Abstract Avatar Z* consists of the whole hand geometry with primitive types. The palm of the hand is represented by an ellipsoid. The total volume of the geometry is smaller than the detailed hand.

The average size of the human hand and the fingers can be found in the literature. We use the hand length and width, finger width data from BS EN ISO 7250-1:2010. The rest of the data is calculated using the *Hand Length to Phalange Length Conversion Table* from [13].

4. USER STUDIES

The aim of the experiments was to examine the accuracy of the virtual hand-button interaction with respect to the collision volume of buttons and alternative hand avatars in the VRFS. A pilot study (expert review) was carried out to define the test scenarios. The experimental design was same for each scenario.

Experimental Design

Figure 5. The virtual aircraft cockpit where the experiments took place.

Apparatus— The experiments were conducted using the VRFS system that is described in Section 2. The participants used the hardware components of the system and the physical mock-up. All the user studies took place in the same virtual aircraft cockpit (Figure 5). The participants were located on the left virtual seat.

Participants—All the experiments were performed by 16 right handed persons whose ages were between 23 and 44. Two of the participants were female. A brief introduction to the VRFS and test procedure was given to the participants prior to the experiments. The aim of this introduction was to make sure that the participants would follow the standard behavior and procedure. For example, they were supposed to put their hands on their knees after touching a button, and wait for the next instruction. Also, they were told that their results would not be considered if they did not follow the procedure. None of the participants had an experience with the VRFS. A training was performed to decrease short and long term training effects of the test cases using a different button which was not used in the experiments.

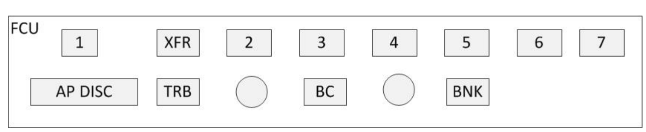


Figure 6. Flight Control Unit (FCU).

Procedure—We calibrated the finger tracking system to the individual participants' hands before conducting the experiments. The participants started with a pseudo-randomized test scenario (eg., collision volume test scenario) and test case (eg., collision volume C test case) to decrease the possible long term training effect on the results. They were only allowed to use their pointing finger. All the participants had long breaks between the test scenarios and short breaks between the test cases to decrease the effect of tiredness on the test results. Also, the break time for the participants was standard and they were only allowed to close their eyes during the short breaks, whereas they were allowed to put the HMD off during the long breaks. The participants were asked to touch the buttons on the FCU (Figure 6) for the objective test cases. In each test case, the participants touched 7 buttons with two runs. There was a 30 seconds gap between each run. In total, they touched 14 buttons for a test case. The order of the buttons which they touched was pseudo-random. Each button was pressed once in a run. The participants were only allowed to touch buttons after an instruction given by the test instructor. During the interaction, the participants were only using a sphere located at the tip of their fingers as a bounding volume of distal phalanx for the collision detection to interact with the virtual buttons but they were not informed about this fact before the tests.

Analysis of Experiments—The test information was recorded with the time stamps and ID of the participants. The hit rate was measured from the recorded raw data. The hits, such as touching the same target button twice, touching another buttons while the target button was instructed and missing the target button were counted as a miss. The results which included the elapsed time were examined after the experiments. The elapsed time data was only used for the measurement of the multiple hits.

Pilot Study (Expert Review)

The pilot study was conducted by four persons who were familiar with the VRFS before the comprehensive experiments (the experiments with 16 participants). The experts, who were human factors specialists and aerospace VR system developers, designed the experiments as described in the previous section. The aim of the pilot study was to prepare test cases and create the test procedure. The test procedure covered the detailed instructions. Also, the experts detected and solved various problems that might occur during the user studies.

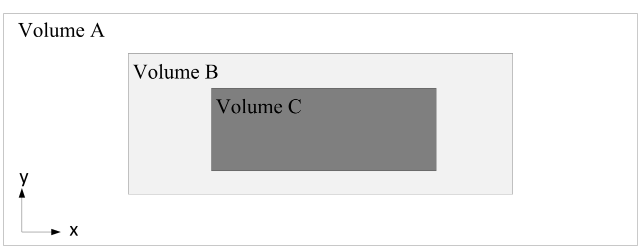


Figure 7. The volume B represents the real volume of the button. The volume A has 150% area of the button and the volume C has 50% area of the button in two dimensional coordinate system.

The experts also performed the experiments before the comprehensive tests. Actually, the pilot study was a mini version of these experiments. Therefore, they followed the same test procedure which was explained in the previous section.

As an initial study, we tested the accuracy of the hand-button interaction. Firstly, we measured the hit rate of each avatar. The mean values of the hit rates were 54% (Avatar X), 50% (Avatar Y), 79% (Avatar Z), and 86% (detailed hand). We observed that the hit rate increased as the volume and details of the hand avatar increased within certain limits. Secondly, we measured the hit rate of different collision volumes. The mean values of the hit rates for different collision volumes A, B, and C (Figure 7) were 66%, 84%, and 68% respectively. We observed that a change in the collision volume of a button did not have a positive effect on the interaction. Accordingly, we prepared *the effect of different hand avatars* and *the effect of collision volume* scenarios to prove these findings statistically. The experts did not take part in these test scenarios and the results of the pilot study were kept apart from the other results.

The pilot study was not only performed to create test scenarios. It was also created to examine possible errors in the experimental setup. If the results of the comprehensive experiments were inconsistent with the pilot studies, this could give us a sign to review the experimental setup and repeat experiments.

The Effect of Different Hand Avatars

Description of the Scenario— The hand avatar Y and the detailed hand avatar were chosen to test the effect of the hand geometry during the interaction with the virtual buttons as a result of the pilot study. Two objective test cases were prepared to prove our finding and one subjective test case was prepared to examine the user perception of appearance, movement and comfort of the hand avatars.

A questionnaire was prepared for the subjective test case. Likert scale, which is commonly used in research area for questionnaires [14] for the subjective user interface tests, was used. The participants rated five-level Likert item (5: very good, 1: very poor). The questions in the questionnaire were based on the appearance, movement and comfort of the hand avatars. The questionnaire was filled out by the participants after completing the whole test scenarios. Besides, they were asked to make comments about their experience afterwards.

The subjective test case was performed within three instructions at the end of the whole test scenarios. First, they were asked to look at their hand in a static position. Then, they were asked to look at their hand while their hand was moving. Finally, they touched the buttons and the seat handle to see the functionality of the hand avatars.

The objective tests were applied as described in the experimental design section. The volume of the button was used as the collision volume. Each objective test case measured the hit rate of each avatar. All the setups for the test cases were the same except the visual geometry of the hand avatar in the virtual environment.

The order of the objective test cases was pseudo-random. Since the test scenarios also had the pseudo-random order, this scenario had more long term training effects than the other test scenario. Therefore, the hit rates were relatively high.

The hand avatars had the same collision volume, shading and color. However, each of them had a different geometry and volume. Therefore, if there was a significant difference between the hit rates of the hand avatars, this might be because of their volume and geometry.

Results—We had subjective and objective test cases in this test scenario. The subjective test case was evaluated using a questionnaire based on the feed-back of the participants related to appearance, comfort and movement of the hand models.

Table 1. Mean values of the subjective test cases for the hand avatars. 5 is rated as very good, 1 is rated as very poor.

	Detailed Hand	Abstract Avatar Y
Comfort	3.56 ($\sigma = 0.81$)	3.63 ($\sigma = 1.08$)
Appearance	3.44 ($\sigma = 1.62$)	3.31 ($\sigma = 0.87$)
Movement	3.44 ($\sigma = 0.96$)	3.38 ($\sigma = 1.14$)

The subjective test results were compared by using a F-test under 95% confidence interval. The comfort of the hand geometries did not significantly differ from each other. The results were also same for the appearance and movement test cases and there was no significant difference between the different hand avatars for the appearance (p = 0.082) and movement (p = 0.25) test cases (Table 1).

Table 2. Mean hit rate for each hand avatar.

	Mean Value
Detailed Hand Avatar	0.77 ($\sigma = 0.19$)
Avatar Y	0.63 ($\sigma = 0.20$)

The objective test results were analyzed as we described in the experiment design section. The mean values of the results were compared by paired samples t-test. A significant difference ($p = 0.02$) between the hit rates of the detailed hand avatar and the hand avatar Y was observed. The detailed hand avatar demonstrated a 77% hit rate while the hand avatar Y was achieving a 63% hit rate. The mean values of the groups differed up to 14% hit rate (Table 2).

The Effect of Collision Volume of the Virtual Buttons

Description of the Scenario—In this user study, we investigated how we could have more effective interaction with the virtual buttons by changing their collision volume. We did not change the design or the real size of the virtual buttons. The visual appearance of the buttons was the same for the different collision volumes. This user study was a typical case study of Fitt's law. According to Fitt's law [15], the collision volume of a button would have an effect on the interaction within certain limits. We chose the limits according to the design of the virtual cockpit. The size of a button does not differ extremely for each cockpit. For example, it is not expected to have a $100x100x10$ mm^3 or $1x1x10$ mm^3 button volume. It is obvious that choosing bigger collision volumes can improve the task performance. However, it is not possible to choose very big collision volumes, since the collision volume of a button can intersect with another button.

In the effect of *collision volume of the virtual buttons scenario*, we used different collision volumes which virtual buttons could have. So that, the collision volume was not so big that it did not intersect with another button and it was not too small that users might not touch it. We created three different collision volumes for this test scenario. Each collision volume was a test case. In Figure 7, the sizes A ($22,5x15x10$ mm^3), B ($15x10x10$ mm^3) and C ($7,5x5x10$ mm^3) represent the collision volumes created for the test scenario. The collision volume B had the same dimensions as the virtual button. The collision volume A was the biggest collision volume that did not intersect with the collision volume of the other buttons. We did not change the depth of the collision volume since it could directly affect the functionality of the button.

In this scenario, the participants were not able to see the collision volume of the buttons. As a result, no subjective tests were performed since it was not possible to collect qualitative subjective data with scales.

Our aim was to see the effect of the collision volume during the interaction. If the interaction with a button which had $15x10x10mm^3$ collision volume was precise, then an increase in the collision volume would not increase the hit rate although smaller collision volume might decrease the hit rate.

Table 3. Mean hit rate for each collision volume.

	Mean Value
Volume A	0.64 ($\sigma = 0.22$)
Volume B	0.66 ($\sigma = 0.22$)
Volume C	0.59 ($\sigma = 0.25$)

Results—The mean value of these objective test results was used to evaluate each test case. We compared the results for the statistical significance by Kruskal-Wallis H test with 95% probability threshold. There was no significant difference among the hit rates of the collision volumes A, B, and C (p = 0.65) (Table 3). The collision volume B had slightly better performance than the collision volume A and C.

5. DISCUSSION

The results from the pilot study and comprehensive experiments were consistent with each other. All the participants followed the experimental procedure and there were no problems due to the hardware or the software during the experiments.

In general, the hit rates of the participants were around 70% during the user studies. This hit rate might not be enough for a realistic interaction with the virtual buttons. However, we observed a steep learning curve. Some of the participants experienced less than a 30% hit rate in the training section and they ended up more than a 60% hit rate before they started the experiments. Long term training effects were relatively weak. The learning curve reflected to the results but statistically this had no effect since the distribution of the compared test cases was pseudo-random.

One reason for the misses was the multiple hits. 65% of the miss hits was due to the multiple hits on the target button. All participants hit the target button more than one time. The most likely cause of the multiple hits was that we had no physical mock-up for the virtual buttons. The participants' finger was going through the buttons since the motion of the virtual hand was not constrained by a physical object. We could use a physical mock-up as a solution. On the other hand, adapting the physical mock-up to different cockpits was problematic and expensive. This would also make the VRFS partly dependent on the aircraft type. We could also provide electrotactile feed-back to the participants. However, this solution might reduce the naturalness of the interaction.

The other reason for the misses was the wrong button hits. 35% of the miss hits was due to the touching wrong button. The cause of the wrong buttons hits could be that the participants could not perceive the depth cues well. Also, Mc Allister demonstrated that $18\ \%$ of the people have difficulties perceiving the stereoscopic images [16]. However, the wrong button hits cannot be only explained by stereoscopic cues. There are various factors, such as visual perception of the participants and stress effects. Further analysis regarding the wrong button hits will be done in the future work.

The collision volume of the virtual button was not a major factor during the virtual hand-button interaction. We did not observe a significant increase in the hit rate with the button collision surface area A ($22, 5x15mm^2$), unlike Steve et. al. who carried out similar research related to the button surface sizes ($14x14mm^2$ and $20x20mm^2$) on the 2D interfaces [1]. The bigger collision volume increased the wrong button hits. On the contrary, it helped the participants touch the target button. In other words, larger target size in the virtual environment did not improve performance. In contrast, Fitts' Law predicts that there would be differences. The wrong button hits can explain this since they were proportional to the button size. On the other hand, we observed a non-significant decrease in the hit rate with the collision area C ($7, 5x5mm^2$). A possible reason might be that the hit rate difference among the collision volumes were so small that the error rate during the measurement did not allow us to detect a statistical significant difference. It showed that increasing the collision volume of a button would not have an impact on the hit rate in the virtual cockpit due to its design.

The detailed hand avatar showed a significant hit rate in the different hand avatars scenario. The hand avatar Y had the lowest hit rate among the whole test scenarios which employed natural collision volume of the virtual button (the collision volume B). Although the hand avatar Y provided a better view of the cockpit gadgets in the limited field of view, the participants had less depth perception with it since the geometry was smaller relative to the detailed hand avatar. Moreover, it provided less visual feed-back to the participants due to its geometry. This result might be due to depth cues since [8] also mentioned that the transparent hand which provides less depth perception causes reduced control over the hand. On the other hand, some participants reported that they had a better view of the cockpit with the hand avatar Y.

The subjective test results showed that most of the participants were comfortable with the hand avatars. However, the comfort of the different hand avatars was not a significant parameter. There was no significant difference subjectively in terms of the appearance and movement of the hand avatars as well. According to [5], a high realism level of limb visualization improves the subjective feeling of control and comfort. If the hand avatar Y was realistic, the participants would have a significant feeling of comfort for the detailed hand avatar. From subjective test results, we can conclude that the task performance of selected hand avatars (detailed hand avatar and hand avatar Y) might not be dependent on the realism but the represented volume and detailed visualization of the hand avatar.

Our findings with regard to the hand avatars might have an impact on a wide range of applications. In robotics, VR applications are employed to control robots with a virtual hand which is a human-hand avatar or a robot-hand avatar. Our findings suggest that a simplistic robot avatar might have less task performance [17] than a detailed hand representation. Besides the robotics, VR applications also help the medical area where hand avatars are constantly employed. They are used for various purposes, such as treatment of amputees (rehabilitating phantom limb pain) [18] and design of prothesis [19]. The developers of such applications employ simplistic or abstract hand avatars. Our findings support that simplistic or partly visualized hand avatars might have a negative effect on these VR applications and their results.

6. Conclusion

This paper has introduced the different aspects of the virtual hand-button interaction without haptic feed-back. The interaction method and its implementation are explained. We have concluded from the user studies that the task performance of the virtual hand-button interaction is more dependent on the hand avatar than the collision size of a button.

We have presented an alternative solution to the problem where the concealment of virtual objects by virtual hands makes interaction difficult. Representing a virtual hand with different granularities can be beneficial to have a better view of virtual cockpit objects, however our result shows that it has a negative effect on the interaction as the virtual transparent hand. We have observed that as the volume and details of the hand avatar decrease, the virtual hand-button interaction becomes less efficient. The comprehensive experiments statistically proved that abstract hand avatars can reduce the task performance.

We have demonstrated that the change of collision volume does not have a positive effect on the virtual hand-button interaction in the virtual cockpit environment. The participants achieved the most efficient interaction with the collision volume of a button which was as same as its visual volume.

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References

[1] N. T. Steve, H. C. Alan, and K. Chen, "A study on touch screen numeric keypads: Effects of key size and key layout. in proceedings of the international multiconference of engineers and computer scientists," in *Proceedings of the International MultiConference of Engineers and Computer Scientists*, vol. II, Hong Kong, March 2013.

[2] B. Lok, S. Naik, M. C. Whitton, and F. P. B. Jr., "Effects of handling real objects and self-avatar fidelity on cognitive task performance and sense of presence in virtual environments." *Presence*, vol. 12, no. 6, pp. 615–628, 2003.

[3] T. Grossman and R. Balakrishnan, "Pointing at trivariate targets in 3d environments," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ser. CHI '04. New York, NY, USA: ACM, 2004, pp. 447–454. [Online]. Available: http://doi.acm.org/10.1145/985692.985749

[4] M. Moehring and B. Froehlich, "Natural interaction metaphors for functional validations of virtual car models," *Visualization and Computer Graphics, IEEE*

Transactions on, vol. 17, no. 9, pp. 1195–1208, Sept 2011.

[5] A. Pusch, O. Martin, and S. Coquillart, "Effects of hand feedback fidelity on near space pointing performance and user acceptance," in *VR Innovation (ISVRI), 2011 IEEE International Symposium on*, March 2011, pp. 97–102.

[6] J. S. Pierce, A. S. Forsberg, M. J. Conway, S. Hong, R. C. Zeleznik, and M. R. Mine, "Image plane interaction techniques in 3d immersive environments," in *Proceedings of the 1997 Symposium on Interactive 3D Graphics*, ser. I3D '97. New York, NY, USA: ACM, 1997, pp. 39–ff.

[7] D. A. G. Jáuregui, F. Argelaguet, and A. Lécuyer, "Design and evaluation of 3d cursors and motion parallax for the exploration of desktop virtual environments," in *IEEE Symposium on 3D User Interfaces 2012, 3DUI 2012, Costa Mesa, CA, USA, March 4-5, 2012*, 2012, pp. 69–76.

[8] V. Buchmann, T. Nilsen, and M. Billinghurst, "Interaction with partially transparent hands and objects," in *Proceedings of the Sixth Australasian Conference on User Interface - Volume 40*, ser. AUIC '05. Darlinghurst, Australia, Australia: Australian Computer Society, Inc., 2005, pp. 17–20.

[9] T. Aslandere, D. Dreyer, F. Pantkratz, and R. Schubotz, "A generic virtual reality flight simulator," in *Virtuelle und Erweiterte Realitt, 11. Workshop der GI-Fachgruppe VR/AR*. Aachen, Germany: Shaker Verlag, September 2014, pp. 1–13.

[10] H. Salzmann and B. Froehlich, "The two-user seating buck: Enabling face-to-face discussions of novel car interface concepts," in *Virtual Reality Conference, 2008. VR '08. IEEE*, March 2008, pp. 75–82.

[11] D. A. Bowman, E. Kruijff, J. J. LaViola, and I. Poupyrev, *3D User Interfaces: Theory and Practice*. Redwood City, CA, USA: Addison Wesley Longman Publishing Co., Inc., 2004.

[12] D.-I. G. Zachmann, "Virtual reality in assembly simulation collision detection, simulation algorithms, and interaction techniques," Ph.D. dissertation, der Technischen Universitaet Darmstadt, 2000.

[13] F. van der Hulst, S. Schatzle, C. Preusche, and A. Schiele, "A functional anatomy based kinematic human hand model with simple size adaptation," in *Robotics and Automation (ICRA), 2012 IEEE International Conference on*, May 2012, pp. 5123–5129.

[14] M. C. Kaptein, C. Nass, and P. Markopoulos, "Powerful and consistent analysis of likert-type ratingscales," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ser. CHI '10. New York, NY, USA: ACM, 2010, pp. 2391–2394.

[15] I. S. MacKenzie, "Fitts' law as a research and design tool in human-computer interaction," *Human-Computer Interaction*, vol. 7, no. 1, pp. 91–139, 1992.

[16] D. F. McAllister, Ed., *Stereo Computer Graphics: And Other True 3D Technologies*. Princeton, NJ, USA: Princeton University Press, 1993.

[17] H. Kawasaki, K. Nakayama, T. Mouri, and S. Ito, "Virtual teaching based on hand manipulability for multi-fingered robots," in *Robotics and Automation, 2001. Proceedings 2001 ICRA. IEEE International Conference on*, vol. 2, 2001, pp. 1388–1393 vol.2.

[18] A. Zweighaft, G. Slotness, A. Henderson, L. Osborne, S. Lightbody, L. Perhala, P. Brown, N. Haynes, S. Kern, P. Usgaonkar, M. Meese, S. Pierce, and G. Gerling, "A physical workstation, body tracking interface, and immersive virtual environment for rehabilitating phantom limb pain," in *Systems and Information Design Symposium (SIEDS), 2012 IEEE*, April 2012, pp. 184–189.

[19] N. Bunderson, "Real-time control of an interactive impulsive virtual prosthesis," *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, vol. 22, no. 2, pp. 363–370, March 2014.

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