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ORIGINAL PAPER

# Integration and evaluation of haptic feedbacks: from CAD models to virtual prototyping

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**Abstract** This paper studies the benefits that haptic feedback can provide in performing complex maintenance tasks using virtual mock-ups. We have carried out user study that consisted on two experiments where participants had to perform an accessibility task. A human-scale string-based haptic interface was used to provide the operator with haptic stimuli. A prop was used to provide grasp feedback. A mocap system tracks user's hand and head movements while a 5DT data-glove is used to measure finger flexion. In the first experiment the effect of haptic (collision) and visual feedback are investigated. In the second experiment we investigated the effect of haptic guidance on operator performance. The results were analyzed in terms of task completion time and collision avoidance. Experiments show that haptic stimuli proved to be more efficient than visual ones. In addition, haptic guidance helped the operators to correct trajectories and hence improve their performance.

**Keywords** Virtual environment · Virtual mock-up · Haptic feedback · Virtual guide · Human performance

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## 1 Introduction

Nowadays, car manufacturers use computer aided design (CAD) to reduce costs, time-to-market and to increase the overall quality of products. In this context, physical mock-ups are replaced by virtual mock-ups for accessibility testing, assembly simulations, operation training etc. In such simulations, sensory feedback must be provided in an intuitive and comprehensible way. Therefore, it is of great importance to investigate the factors related to information presentation modalities that affect human performance. In situation involving complex virtual mock-ups, it may be useful to provide the operator with some sorts of guidance that facilitates task accomplishment. For example, virtual fixtures or haptic guides have been proved to be efficient in tele-manipulation [24] or selection of objects in virtual environments [31]. Both accessibility testing and assembly simulations are interactive processes involving the operator and the handled objects, and hence simulation environments must be able to react according to the users actions. Moreover, the haptic interface must be as transparent as possible in order to provide the operator with realistic interaction with the virtual mock-up.

In this paper, we investigated the benefits that haptic feedback can provide in performing complex tasks using virtual mock-ups. We have carried out user study that consisted on two experiments where participants had to perform an accessibility task. A human-scale string-based haptic interface was used to provide the operator with haptic stimuli. A prop was used to provide grasp feedback. A mocap system tracks user's hand and head movements while a 5DT data-glove is used to measure finger flexion. The results were analyzed in terms of task completion time and collision avoidance.

Section 2 surveys the related work. Section 3 presents the CAD to VR methodology implemented. In Sect. 4, we describe the virtual environment (VE) that allows human-scale haptic interaction with virtual mock-ups. In Sect. 5, the experimental study and the results are presented. The paper ends by a conclusion and gives some tracks for future work.

## 2 Related work

In order to immerse the user in virtual worlds, stereoscopic techniques were developed. Several studies prove the benefits of binocular disparity enhance the visual depth perception. Hence stereoscopic visualization contributes to understand spatial relationships and discriminate objects [33]. The use of stereo improves both accuracy and time reaction in tasks such as navigation, manipulation or even educational training. Through the years, new stimuli have been introduced in virtual environments in an attempt to improve the overall perception. Some other visual cues such motion parallax may be very efficient, even in the absence of stereoscopic cues.

Several studies have dealt with multisensory interaction in haptic systems. In [20], a good introduction to multisensory processing is given and in [29], multi-sensory perception is studied more widely.

Some studies have analyzed in particular, the benefits of adding auditory feedback to haptic systems. DiFranco et al. [8] showed how auditory stimuli of pre-recorded tapping sounds influenced on the stiffness perception of the virtual objects. In [19], a combination of haptic and auditory feedback was proposed as a solution to increase the quantity and quality of available textural information. In the same field, [12] suggested that users could be influenced by auditory input on surface textural perception. Apart from auditory stimuli, visual cues had also been used to alter haptic perception. For instance, [28] showed how visual stimuli could modify the stiffness perception of a virtual spring. Early studies focused on objective measures of accuracy and time to completion. For instance in pick and place tasks, time to completion was shown to either improve with the addition of force feedback [22]. Richard et al. [23] have investigated the effect of haptic, visual and auditive force feedback on dextrous manipulation performance when interacting with virtual objects. They found that although visual and auditive feedback allowed to improve subjects' performance, force feedback was the best modality.

A survey of the haptic interface devices developed so far can be found in [1,2,5,7]. Most of these haptic interfaces are used for industrial applications in which immersion and presence is not crucial. Indeed, they are intrusive, expensive and have a limited workspace [25]. Moreover, although many industrial tasks are bimanual, these interfaces involve the use of only one hand [9,14,25]. Attempts to add force feedback to large-scale virtual environments have been proposed such as one from the University of North Carolina [2,3], and work from the University of Utah [11]. Both approaches are in fact quite similar. Both employs a one-screen workbench and propose installing an arm-type force feedback device. More recently, Lécuyer et al. experimented with a portable haptic device, which could follow large-scale users displacements in front of a two-screen workbench [18]. This interface called the Wearable Haptic Handle (W2H), developed by CEA, is made of two parts. The upper part is a small platform, which moves in 6 Degrees of Freedom (DoF) actuated by a wire driven based Stewart platform. The user feels the displacements of the platform through his/her hand while interacting with the virtual environment. The W2H has a wide workspace, which can match the large visualization space of the workbench and is small enough not to obstruct the users field of view. A floor-grounded haptic device for aircraft engine maintainability (LHIfAM) has been recently developed [27]. This device is used to track hand movement and provides force feedback within a large workspace. Other kinds of haptic interfaces were evaluated for education, entertainment and industrial applications [4,6,26,30,32]. These alternative interfaces are composed of actuators providing a force through a set of strings adequately linked together or to a manipulation tool [10,13,15–17]. A quick look at such interfaces shows that most of them have very interesting properties i.e. fixed-base, large workspace, and low intrusion. Additional properties like lightness, safeness, or low cost are also satisfied. However, these interfaces are complex to set-up and not easy to control. Paljic and Coquillart proposed a passive stringed-based haptic feedback system that can provide the user with grounded forces in a 3D manipulation space [21]. This interface uses brakes instead of motors and is easier to control, but it cannot simulate variable force feedback and therefore interaction with deformable virtual objects.

## 3 CAD-to-VR methodology

The proposed CAD-to-VR methodology involves different steps (illustrated in Fig. 1), such as model simplification (1), model integration (2–3). The graphical model is used for visual display of the virtual mock-up (4), while the physical one is used for both tactile and kinaesthetic feedback (5–6). Our methodology for model simplification allows to decrease the number of polygons of the CAD models while keeping the same level of visual quality. Model integration allows to obtain both graphical and physical models of CAD data. Physical models are built using NovodeX$^{TM}$.

## 4 Virtual environment

According to their sizes, we could divide VEs into two categories: small-scale or desk-top VEs and human-scale VEs.

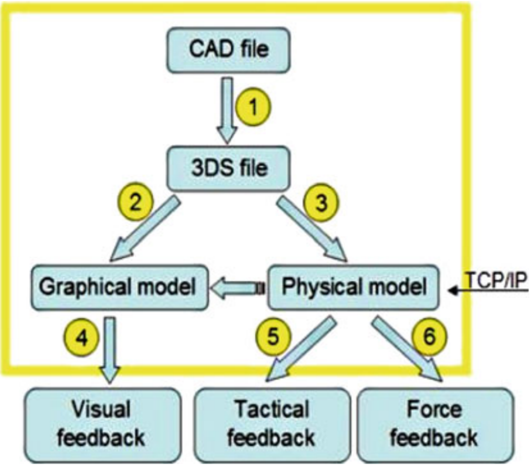

**Fig. 1** Schematic of the CAD-to-VR methodology

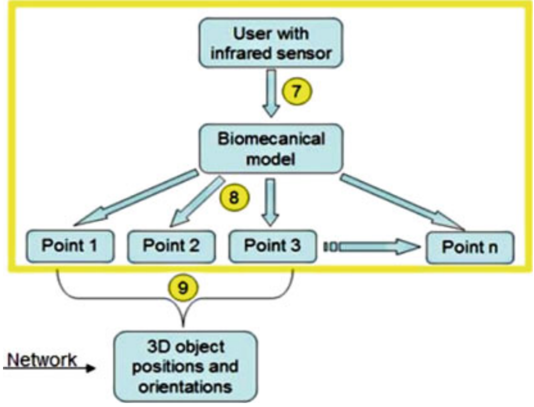

**Fig. 2** Schematic of human interaction using the mocap system

Desk-top VEs include all situations where the user is sitting still in front of a desktop monitor or wearing a Binocular Omni-Orientation Monitor. These kinds of VEs generally constrain user movements within a small workspace. In large-scale accessibility and assembly simulations, the operator needs to operate and interact with virtual objects in a large workspace. In this section we present our experimental human-scale VE that provides force feedback using the SPIDAR system (Space Interface Device for Artificial Reality) [17]. virtual images are displayed on a rear-projected large screen (2 × 2.5 m).

The graphical and physical models of the human operator are both integrated according to the schematic shown in Fig. 2. A biomechanical model is used for the animation of operator's hand and arm (7). In order to get accurate position and orientation tracking of the user, an infrared camera-based motion capture system is used. Five reflected markers are placed on the operator's body (8): three markers on the data-glove to assess hand position and orientation (9), one marker on a cap worn by the operator for head tracking, and one marker on the operator's arm.

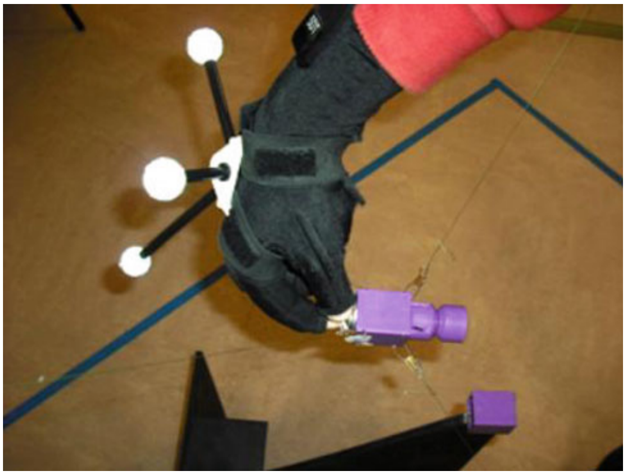

**Fig. 3** Illustration of the prop based user interface integrated into a SPIDAR system. Reflective balls have been mounted on a 5DT dataglove

Our large-scale VE provides force feedback using the SPIDAR system. The SPIDAR system uses a SH4 controller from Cyverse. In order to provide force feedback to both hands, a total of 8 motors are placed on the corners of a cubic frame surrounding the user. In order to provide haptic grasping feedback to the operator, a prop (see Fig. 3) was used [5].

## 5 Experimental study

### 5.1 Setup and procedures

In each experiment, twelve volunteer students participated. They were naive in the use of virtual reality techniques. In the first experiment, each participant was instructed to (1) access a lamp in the virtual mockup, (2) extract the lamp, and (3) place the lamp in its original position, in the following three conditions:

- C1: no additional feedback,
- C2: additional visual feedback (colour),
- C3: haptic feedback (SPIDAR).

The task has to be repeated three times for each condition. Conditions were presented in different order to avoid any training transfer. In C1, there is no feedback in case of collision. In C2, there is a color feedback in case of collision. The part affected turns to red. In C3, there is a force feedback. A repulsive force avoid the penetration.

Poor grasp of the prop or a bad calibration due to unexpected movements may cause problems of feedback coherency between grasping (prop) and simulated forces (SPIDAR). In order to avoid this drawback, three interaction

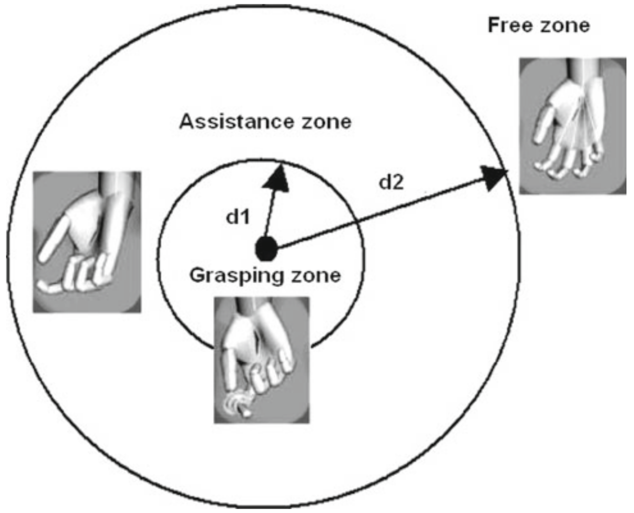

**Fig. 4** Illustration of the three interaction zones used with distinct characteristics

zones have been defined (Fig 4). In the first zone (free zone), the virtual hand fully reproduce operator's hand movements measured using the 5dT data-glove. In the second zone (assistance zone, $d_1 = 10\,\text{cm}$), the virtual hand is no more animated and reflects an appropriate hand gesture for grasping the lamp. In the final zone (gasping zone, $d_2 = 5\,\text{mm}$), the lamp is automatically attached to the virtual hand.

In the second experiment, the participants were instructed to (1) extract the lamp from the mock-up, and (2) place it in its original position inside the mock-up. This task was performed in the following two conditions:

- C1: no additional feedback,
- C2: with haptic guide (SPIDAR).

The task has to be repeated six times for each condition. Conditions were presented in different order to avoid any training transfer. In C1, there is no feedback in case of collision. In C2, a haptic guide helps the user to perform the task. The virtual guide consists of an attractive force oriented towards the initial position of the lamp. The magnitude of the force depends on the distance of the current position of the virtual lamp and the initial position of the lamp according to Hook's law. The force is activated when the user enters in the assistance zone and deactivated in the grasping zone defined in Fig. 4.

Participants were in front of the large rear-projected screen at a distance of approximately 1.5 m. They worn a 5DT data glove equipped with three reflective balls (Fig. 5). In order to get acquainted with the system each participant performed a pre-trial of the task in C1 condition. For both experiments the following data were collected.

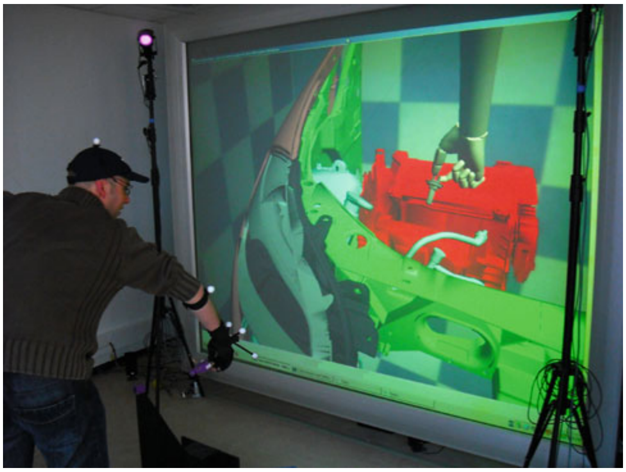

**Fig. 5** Illustration of a user performing the task

- Task completion time,
- Number of collisions,
- Subjective response via questionnaire.

The experimental set-up is illustrated in Fig. 5. The user interaction with the virtual mock-up using the camera-based mocap system. Global force feedback is provided using the SPIDAR system. Local (grasp) feedback is achieved using the prop.

## 5.2 Experiment I: effect of multimodal feedback

The aim of the first experiment was to find the best sensorial modality among two (visual and haptic). Only one factor is used. So, the proposed experimental design does not make use of advanced methods such as the Tagushi method.

### *5.2.1 Results and analysis*

Results were analyzed through ANOVA. We examine the effect sensory feedback on (a) task completion time and (b) number of collisions. Then, we look into the learning process associated with the different sensory feedback.

*Task completion time* Results, illustrated in Fig. 6, revealed that sensory feedback has a significant effect on task completion time: ($F(2, 11) = 27.95$; $p < 0.05$). A statistical difference between conditions C1, C2 and C3 was observed. In C1 condition the average completion time was 30.34 s (STD = 3.1). Average completion time was 26.45 s (STD = 1.8) for C2 (additional visual feedback) and 22.24 s (STD = 3.4) for C3 (haptic feedback). Thus visual and haptic feedbacks allow increasing performance, as compared with the open-loop case (no additional feedback), by 12.8 and 16%, respectively. Haptic feedback increase performance by

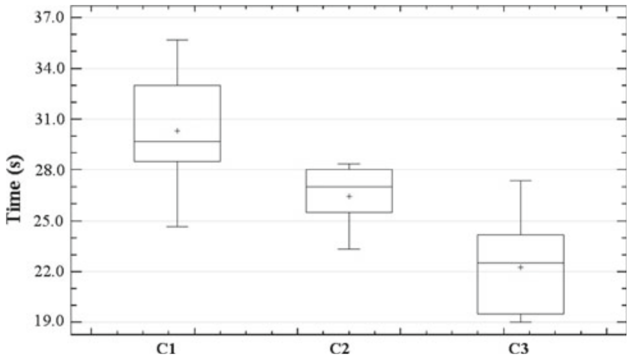

**Fig. 6** Completion time versus conditions

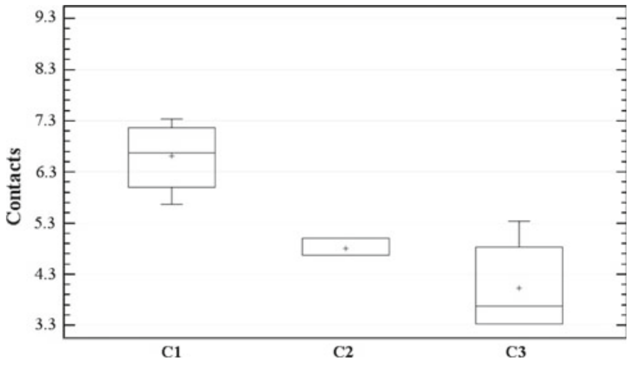

**Fig. 7** Number of collisions versus conditions

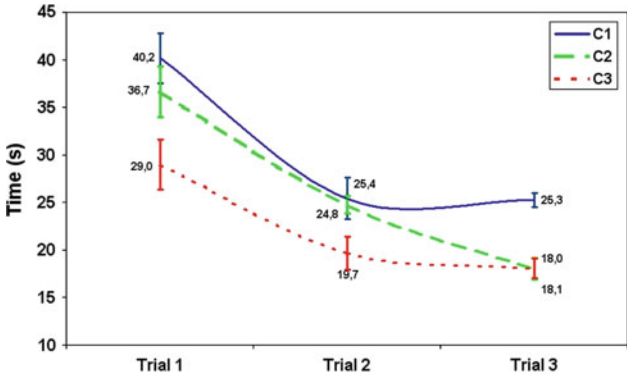

**Fig. 8** Learning process associated with time

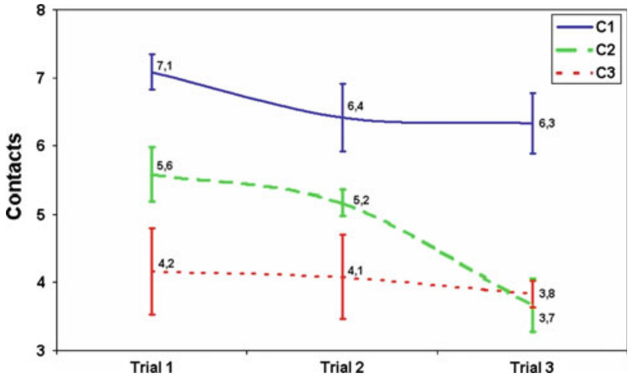

**Fig. 9** Learning process associated with contacts

15.6% as compared to additional visual feedback. However, participants' performance was more disparate.

*Number of collisions* Results, illustrated in Fig. 7, revealed that sensory feedback has a significant effect on the number of collisions: ($F(2, 11) = 44.76$; $p < 0.05$). As previously, a statistical difference between C1, C2 and C3 conditions was observed. In C1 the average number of collisions was 6.61 (STD = 0.58). The average number of collisions was 4.80 s (STD = 0.15) for C2 and 4.03 (STD = 0.8) for C3. Thus visual and haptic feedbacks led to a significant reduction of the number of collisions as compared to the open-loop case, by 27.3 and 39.0%, respectively. Haptic feedback increase performance by 16.2% as compared with additional visual feedback. As for task completion time, participants' performance was more disparate in condition C3.

*Learning process* The learning process is defined here by the improvement of participant performance associated with task repetitions. We analyzed the learning process associated with both task completion time and number of collisions. Although each participant repeated the task three times only, a learning process was observed for all conditions (Fig. 8). Average task completion time was 40.2 s at the first trial and 25.4 s at the last trial for condition C1, 36.7 s at the first trial and 18.1 s at the last trial for condition C2, and 29.2 s at the first trial and 17.9 s at the last trial for condition C3. This results in a performance improvement of about 37, 50, and 48% for conditions C1, C2 and C3, respectively.

Concerning the number of collisions, we observed a poor learning process for each condition. This result is not very surprising for C1 condition since no feedback was displayed for collisions. In the C3 condition, participants were good at the first trial. This shows that the haptic interface is user-friendly and efficient. The poor learning process associated with C2 condition may be explained by the lack of spatial information as is it the case with force feedback (sensation of force direction during collision) (Fig. 9).

*Subjective evaluation* In order to have subjective evaluation, we collected the user's responses through a questionnaire. The user's responses for each question are the following:

1. What condition did you prefer? (C1, C2, C3)
   Here 25% of the subjects preferred condition C2 (visual feedback) while 75% were in favor of condition C3 (force feedback).
2. Do you think that haptic feedback (using our experimental configuration) is effective for this task?

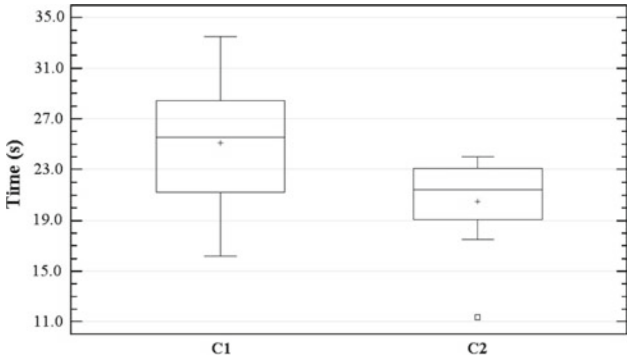

**Fig. 10** Completion time versus conditions

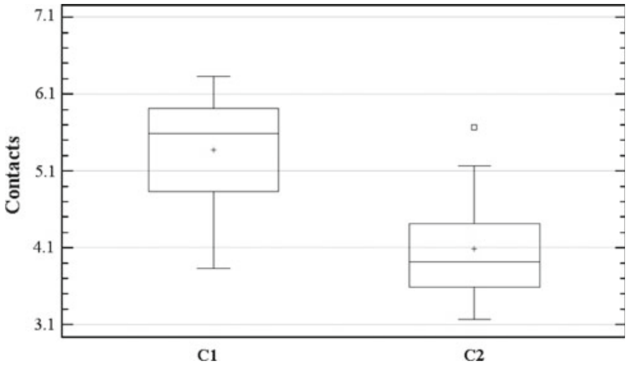

**Fig. 11** Number of collisions versus conditions

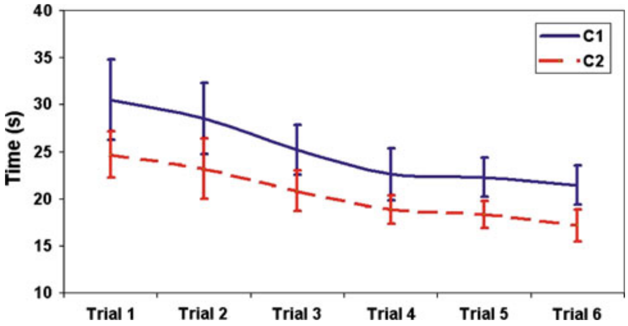

**Fig. 12** Time: learning process associated with all conditions

91.66% of the users responded "yes" while the remaining 8.33% users responded "no" to this question.

3. Which part of task was the most difficult?
   - Accessing the lamp,
   - Grasping the lamp,
   - Extracting the lamp,
   - Reinserting the lamp.

   For 25% of the users accessing the lamp was the most difficult task, while 33.33, 16.66 and 25% users opted for grasping, extraction and reinsertion, respectively, as the most difficult part of the task.
4. Which feedback helped you more in task accomplishment?
   - Visual feedback,
   - Haptic feedback.

Here 16.66% of the users' response was for visual feedback while 83.33% opted for force feedback.

## 5.3 Experimental II: effect of haptic guide

The aim of this experiment is to examine the effect of an haptic guide on human performance in the task involving extraction and replacement of a car's lamp in the virtual car mock-up. As in the first experiment, one factor is used. So, the proposed experimental design does not make use of advanced methods such as the Tagushi method.

### *5.3.1 Results and analysis*

Results were analyzed through ANOVA. We examine the effect of haptic guide on (a) task completion time and (b) collision time. Then, we look into the learning process.

*Task completion time* Results, illustrated in Fig. 10, revealed that haptic guide has a significant effect on task completion time: $(F(1, 11) = 14.58;\ p < 0.005)$. A statistical difference between conditions C1 and C2 was observed. In C1 condition the average completion time was 25.07 s (STD = 5.28). Average completion time was 20.5 s (STD = 3.54) for C2 (haptic guide). Thus haptic guide allow increasing performance, as compared with the open-loop case (no additional feedback), by 18.23%.

*Number of collisions* Results, illustrated in Fig. 11, revealed that haptic guide has a significant effect on the number of collisions: $(F(1, 11) = 66.99;\ p < 0.005)$. As previously, a statistical difference between C1 and C2 conditions was observed. In C1 the average number of collisions was 5.37 (STD = 0.75). The average number of collisions was 4.08 (STD = 0.75) for C2. Thus haptic haptic guide led to a significant reduction of the number of collisions as compared to the open-loop case, by 24.0 %.

*Learning process* The learning process is defined here by the improvement of participant performance associated with task repetitions. We analyzed the learning process associated with both task completion time and number of collisions. Although each participant repeated the task six times only, a learning process was observed for all conditions (Figs. 12, 13). Average task completion time was 30.5 s at the first trial and 21.41 s at the last trial for condition C1, 24.7 s at the first trial and 17.2 s at the last trial for condition C2. This results

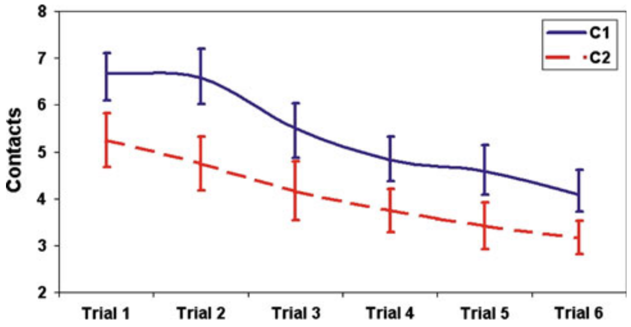

**Fig. 13** Contacts: learning process associated with all conditions

in a performance improvement of about 29.84 and 30.37%, for conditions C1 and C2, respectively.

Concerning the number of collisions, we observed 6.7 at the first trial and 4.1 at the last trial for condition C1, 5.25 at the first trial and 3.2 at the last trial for condition C2. This results in a performance improvement of about 38.81 and 39.05%, for conditions C1 and C2, respectively.

*Subjective evaluation* In order to have subjective evaluation, we collected the user's responses through a questionnaire. The user's responses for each question are the following:

1. What condition did you prefer? (C1, C2)
   Here 83% of the subjects preferred condition C2 (with haptic guide) while 17% were in favor of condition C1 (without haptic guide).
2. Do you think that haptic guide provides an effective guidance?
   91% of the users responded "yes" while the remaining 9% users responded "no" to this question.
3. Which part of task was the most difficult? (accessibility, grasping, extraction, replacement)
   For 75% of the users the reinsertion of the lamp was the most difficult while for 25% it was the lamp's extraction.
4. Do you think that head tracking helps in the perception of environment's depth?
   Here 67% users were of the view that head tracking provides no help in the perception of environment's depth, while 33% reported that it provides some help in the mentioned context.

### 5.4 Discussion

Concerning the first experiment, we observed that haptic stimuli proved to be more efficient than visual ones. The impact is significative for the task completion time and the number of collisions during this task. These results are confirmed by the volunteers who favored the force feedback. The learning process for both the completion time and the number of collisions, shows that with sensory feedbacks, the results tend towards a limit. It appears that several other trials should have been done to see the real limit. Indeed, we don't know if the limits on the graphs are due to the ease of the task. Concerning the second experiment, we can see that the haptic guide seems to be efficient. However, the volunteers said that the reinsertion of the lamp was the most difficult part of the task despite the haptic guide. We have to find a better way to perform this part of the task as well as possible. Then, most of the volunteers would have preferred to see the VE in three dimensions: the depth would have been better understood than the one created the head tracking.

## 6 Conclusion and future work

In this paper, we presented a CAD-to-VR methodology that allows the integration of the human operator, and a low-intrusive large-scale virtual environment that allows haptic interaction with virtual mock-up. In this context, we have carried out a user study that consisted on two experiments where participants had to perform an accessibility task. A human-scale string-based haptic interface was used to provide the operator with haptic stimuli. A prop was used to provide grasp feedback. A mocap system tracks user's hand and head movements while a 5DT data-glove is used to measure finger flexion. In the first experiment the effect of haptic (collision) and visual feedback are investigated. In the second experiment we investigated the effect of haptic guidance on operator performance. The results were analyzed in terms of task completion time and collision avoidance. Experiments show that haptic stimuli proved to be more efficient than visual ones. In addition, haptic guidance helped the operators to correct trajectories and hence improve their performance. In the near future some haptic guides (both attractive and repulsive) will be integrated in order to avoid unwanted collisions and help the user while passing complex trajectories inside the virtual mock-ups.

## References

1. Bougilla, L., Ishii, M., Sato, M.: Multi-modal haptic device for large-scale virtual environment. In: 8th ACM International Conference on Multimedia (2000)
2. Brederson, J., Ikits, M., Johnson, C., Hansen, C., Hollerbach, J.: The visual haptic workbench. In: Proceedings of the Fifth PHANToM Users Group Workshop (2000)
3. Brooks, F.P., Ouh-Young, M., Batter, J.J., Kilpatrick, P.J.: Project GROPE-haptic display for scientific visualization, computer graphics. In: Proceedings of ACM SIGGRAPH 90, vol. 24, no. 4, pp. 177–185 (1990)
4. Cai, Y., Wang, S., Sato, M.: A human-scale direct motion instruction system device for education systems. IEICE Trans. **E80-D**(2), 212–217 (1997)

5. Chamaret, D., Richard, P., Ferrier, J.L.: From CAD model to human-scale multimodal interation with virtual mockup: an automotive application. In: 5th International Conference on Informatics in Control, Automation and Robotics (2008)
6. Choi, W., Jeong, S.J., Hashimoto, N., Hasegawa, S., Koike, Y., Sato, M.: A development and evaluation of reactive motion capture system with haptic feedback. In: Proceedings of the FGR04, vol. 37, pp. 851–856 (2004)
7. Coquillard, S., Wesche, G.: The virtual palette and the virtual remote control panel: a device and an interaction paradigm for the responsive workbench. In: Proceedings of IEEE Virtual Reality CRUZ-NEIRA (1999)
8. DiFranco, D.E., Beauregard, G.L., Srinivasan, M.A.: The effect of auditory cues on the haptic perception of stiffness in virtual environments. In: Proceedings of 1997 ASME International Mechanical Engineering Congress and Exposition, pp. 17–22. Dallas, TX, USA (1997)
9. Friconneau, J., Louveau, F.: Virtuose 6d: a new industrial master arm using innovative ball-screw actuators. In: Proceedings of International Symposium on Robotics (2004)
10. Gallina, P., Rossi, A., Williams II, R.L.: Planar cable-direct-driven robot, Part I and II. In: ASME Design Technical Conferences, Pittsburgh (2000)
11. Grant, B., Helser, A.: Adding force display to a stereoscopic head-tracked projection display. In: Proceedings of the VRAIS98, pp. 81–88 (1998)
12. Guest, S., Catmur, C., Lloyd, D., Spence, C.: Audiotactile interactions in roughness perception. Exp. Brain Res. **146**, 161–171 (2002). doi:10.1007/s00221-002-1164z
13. Hashimoto, N., Ryu, J., Jeong, S.J., Sato, M.: Human-scale interaction with a Multi-projector display and multimodal interfaces. In: Proceedings of the PCM04, vol. 3, pp. 23–30 (2004)
14. Hinckley, K., Paush, R., Goble, J., Kassel, N.: Passive real-world interface props for neurosurgical visualization, CHI (1994)
15. Hirata, Y., Sato, M.: 3-Dimensional interface device for virtual work space. In: Proceedings of the 1992 IEEE/RSJ International Conference on IROS, vol. 2, pp. 889–896 (1992)
16. Inglese, F.X., Jeong, S.J., Richard, P., Sato, M.: Human-scale virtual environment for product design. In: Proceedings of Virtual Concept05 (2005)
17. Ishii, M., Sato, M.: A 3d spatial interface device using tensed strings. Presence **3**(1), 81–86 (1994)
18. Luyer, A., Megard, C., Burkhardt, J.M., Lim, T., Coquillart, S., Coiffet, P., Graux, L.: The effect of haptic, visual and auditory feedback on an insertion task on a 2-screen workbench. In: Immersive Projection Technology Symposium (2002)
19. Mc Gee, M.R., Gray, P.D., Brewster, S.A.: Feeling rough: multimodel perception of virtual roughness. In: Proceedings of the 1st Eurohaptics conference, pp. 29–33. Birmingham, UK (2001)
20. Pai, D.K.: Multisensory interaction: real and virtual. In: Dario, P., Chatila, R. (eds.) Robotics Research: the Eleventh International Symposium, vol. 15, Springer tracts in advanced robotics, pp. 489–500. Springer, Berlin Heidelberg New York (2005)
21. Paljic, A., Tarrin, N., Coquillart, S., Bouguila, L., Sato, M.: The Passive Stringed Haptic Spidar for the Worlkbench, Eurographics04 (2004)
22. Richard, P., Burdea, G., Coiffet, P.: Human performance in tasks involving virtual objects with force feedback. In: Proceedings of Interface to Real and Virtual Worlds Conference, pp. 229–238. Montpellier, France (1993)
23. Richard, P., Coiffet, P.: Dextrous haptic interaction in Virtual Environments: human performance evaluation. In: Proceedings of the 8th IEEE Int. Work. on Robot and Human Interaction, pp. 315–320. Pisa, Italy (1999)
24. Rosenberg, L.B.: The use of virtual fixtures to enhance telemanipulation with time delay. In: Proceedings, ASME Winter Anual Meeting on Haptic Interfaces for Virtual environment and Teleoperator Systems, New Orleans, Loisiana (1993)
25. Sandin, D., Defanti, T.: Surround screen projection based virtual reality. In: Proceedings of SIGGRAPH. GARREC (1993)
26. Sato, M.: Evolution of SPIDAR. In: Proceedings of the 3rd International Virtual Reality Conference (2001)
27. Savall, J., Borro, D., Gil, J.J., Matey, L.: Description of a Haptic System for Virtual Maintainability in Aeronautics. In: Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 2887–2892. EPFL, Lausanne, Switzerland (2002)
28. Srinivasan, M.A., Beauregard, G.L., Brock, D.L.: The impact of visual information on the haptic perception of stiffness in virtual environments. In: Proceedings of the 1996 ASME International Mechanical Engineering Congress and Exposition, pp. 555–559. Atlanta, Georgia, USA (1996)
29. Stein, B.E., Meredith, M.A.: The Merging of the Senses. MIT Press, New York (1993)
30. Tarrin, N., Coquillart, S., Hasegawa, S., Bougila, L., Sato, M.: The stringed haptic workbench: a new haptic workbench solution. In: EUROGRAPHICS Proceedings (2003)
31. Ullah, S., Ouramdane, N., Otmane, S., Richard, P., Davesne, F., Mallem, M.: Augmenting 3D interactions with haptic guide in large scale virtual environments. Int. J. Virtual Real. **8**(2), 25–31 (2009)
32. Walairacht, S., Ishii, M., Koike, Y., Sato, M.: Two-handed multi-fingers string-based haptic interface device. IEICE Trans. **E84-D**(3), 365–373 (2001)
33. Yeh, Y.Y., Silverstein, L.D.: Limits of fusion and depth judgment in stereoscopic color displays. Hum. Factors **32**(1), 45–60 (1990)