# Evaluation of a Haptic Environment for Assembly Task Simulation

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**Abstract:** A new application for virtually simulating assembly tasks was developed by integrating multimodal data and kinematic information provided by a mobility module into a Collaborative Virtual Environment. During assembly simulations, the haptic device implemented in the application supports the user's movements by using the automatically detected kinematic constraints between the components of the assembly. Thus, all stages of the assembly process can be simulated, which leads to an increase of the user immersion. The current paper presents the methodology, the protocols and the results of evaluating the application, the test being performed by a group of 20 participants. Tasks were run for assessing the following criteria: usability, efficiency, ease of use and quality of the haptic feedback. Each participant tested the application for two types of assemblies (mounting flange and standard vise) with different complexity and number of components. Testing protocols considered both objective evaluation (using real-time information), as well as subjective evaluation using questionnaires. The analysis of the results proved the feasibility of the proposed approach. Further work will be focused on extensive studies for assessing intra-users variations and improvement of the haptic feedback for a number of particular situations reported by users as important.

**Keywords:** Assembly/Disassembly, Virtual Environment, Haptic Interfaces.

## 1. Introduction

Nowadays, a lot of effort has been made to develop virtual tools for different purposes: cooperative ideas generation (Thorsteinsson, 2010), production optimization (Debevec, 2014), assembly simulation (Seth, 2008), etc. In this context, engineers cannot even consider developing and manufacturing a successful product without the use of 3D Computer-Aided Design (CAD) systems or, more recently, without using Virtual Environments (VEs).

Assembly, as a complex process with high impact on the product development, has been intensively studied for increasing its overall efficiency while maintaining its profitability. In order to achieve these goals, engineers make use of different knowledge, tools and methods (Pupaza, 2014), (Iacob, 2013) for supporting their work and for the early evaluation of their design decisions over the assembly cost and time. Efficient design software applications are offering the possibility to generate and use completely parameterized virtual 3D assembly models for automating activities such as: component design changes propagation within assembly, BoM (Bill of Materials) generation, interference checking or component reuse. Lately, there is a trend in developing software products as add-ons of different 3D CAD systems for generating valid Assembly and Disassembly (A/D) sequences plans, for identifying functional components and for simulating A/D operations, which represent three important aspects not yet completely resolved by the commercial CAD packages. These complex research subjects are also part of the same effort of overall improvement of the design process by transferring the focus on product assembly design, rather than on component design. However, in order to be efficient, these design approaches should consider how the real A/D tasks are performed and try to implement algorithms which avoid generating unfeasible A/D trajectories. In addition, they should provide more realistic boundary conditions than just trajectory extreme points. Although the aid provided by these automatic software tools is important, the final decision belongs to the designer. The applications provide a list of results and, sometimes, a number of criteria for ordering, thus the engineer should be able to check different feasible solutions in order to choose the best one. In this context, we consider that immersive simulations based on data automatically extracted and processed from CAD assembly models can eliminate some of these disadvantages, representing a necessity of the modern engineering design.

Haptic technology can give back engineers the sense of touch that they lose when using CAD products, and combining this with an application focused on generating assembly kinematic constraints, will not only reduce the complexity of collision detection algorithms, but also will provide users' a realistic feeling when simulating assembly and disassembly operations. Therefore, a haptic A/D simulation VE, which can provide information and data regarding valid A/D trajectories (translations, rotations and helical ones) or accessibility trajectories, becomes a more efficient and useful tool for an engineer, during the Product Development Process (PDP) or training. In this sense, we developed an A/D simulation application that implements a mobility module based on kinematic constraints between assembly components in a Collaborative Virtual Environment (CVE). A haptic device was implemented in the application in order to provide the users the possibility to perform A/D tasks in a similar manner as in the real environment, thus increasing the quality of the immersive environment.

The current paper presents the evaluation of this application performed by a group of 20 participants for two types of assembly models: one with a low difficulty (mounting flange) and one with a medium difficulty (standard vise). The experiments were conducted using the Virtuose haptic interface with 6 DoFs (Degrees of Freedom) developed by the French company Haption.

## 2. Evaluation of Immersive Engineering Applications

Usability evaluation is a mandatory activity following the design, development and implementation of any new or improved system, focusing both on the software application and on the equipment (hardware). In this phase, the system is put face-to-face with the user and the task, for testing and for inferring its efficiency, usefulness and satisfaction, using different approaches and criteria. Thus, the studies in this field are usually considering the development of generic usability models (requirements) for the haptic applications and interfaces, as well as on using the usability definitions, factors, classifications and methods, and adapt them to a specific system. Here, a clear distinction should be made between the performance metrics for the haptic interfaces and the performance metrics for the haptic applications, the research presented in our paper being focused on application' performance analysis.

As part of the first category, it can be mentioned the study presented in (Khan, 2013) that investigates and classifies the usability factors and sub-factors (major and minor factors) applicable to haptic systems, the authors concluding that efficiency, effectiveness, satisfaction, learnability and safety are the most important. Also, (Samur, 2007) is presenting a systematic evaluation of haptic interfaces (in terms of rendering realism/fidelity) based on test beds. Having as a starting point the classification of haptic interaction according to task, perception and feedback, the following performance metrics are proposed by authors: travel and selection, selection and manipulation, detection and identification.

The second group of studies is constituted of those which evaluate haptic VE applications based on a set of different assessments criteria.

A comparative analysis of the main features: system performance, modeling approach, collision detection method, assembly path visualization, CAD models import, etc. of several haptic virtual assembly applications is presented in (Gonzalez-Badillo, 2014-a). From this study and those presented further, a systematization of the information regarding the evaluation issues was performed, this being used to fundament our experimental setup and the corresponding test protocols.

In (Lim, 2007) was studied the effect of haptic feedback on the user's ability to execute assembly operations in a VE, by measuring the task completion time parameter. Comparative assessment of performing peg-in-hole task in: real, virtual, virtual and haptic environments, is presented. The results support two conclusions: first, it seems that small assembly features (e.g. chamfers) affect the overall task completion at times when only haptic feedback is provided; and second, that the difference is approximately similar to the values reported for equivalent real world assembly tasks. During experiments, haptic damping effect was also evaluated. User's satisfaction was assessed using the System Usability Scale (SUS).

In (Seth, 2006) is presented SHARP application for A/D tasks (figure 1), which is using a dual-handed touch interface for providing the necessary haptic feedback when performing peg-in-hole task. When collision occurs, the user receives haptic, audio and visual feedback, thus supporting a general decrease of the completion task. Moreover, the testing results showed that, due to the type of geometric representation used, components with low clearances cannot be assembled. This problem is partially solved in (Seth, 2010) by combining physics-based and geometric constraint-based modeling methods for the assembly.

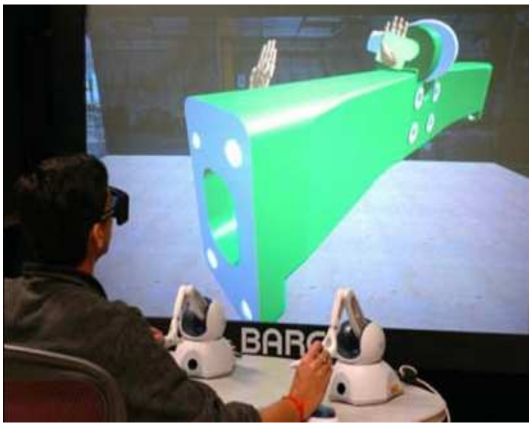

**Figure 1.** Sharp assembly system (Seth, 2006)

In (Bordegoni, 2009) was developed a virtual assembly application in which two parts are mounted using a 6DoFs haptic device. The tasks involved grabbing, holding and then positioning a component, and then grabbing the second component and assembly it with the first one using the same haptic device. The evaluation of the usability of this VE considered criteria like: efficiency and satisfaction, assessed by natural engagement, navigation and orientation support, sense of presence, realistic feedback heuristics.

A Haptic Assembly and Manufacturing System (HAMS) for design, simulation analysis, training and assembly path planning is presented in (Gonzalez-Badillo, 2014-b). The application (figure 2) uses a hybrid approach based on Physics-Based Modeling (PBM) and Dynamic Assembly Constraints (DAC). HAMS is evaluated by considering four assembly tasks. The individual assembly time and mean force are measured in two cases: with PBM, and with PBM and DAC. Also, users were asked to subjectively assess the accuracy of the collision response, being the best evaluated parameter.

Xia et al. developed a haptics-based virtual environment system for assembly training of complex products (Xia, 2012).

**Figure 2.** HAMS assembly interface (Gonzalez-Badillo, 2014)

It includes: projector – DepthQ 3D, 3D glasses, haptics – Phantom Premium, data glove – CyberGlove, tracking – Flock of birds and a prototype of a motion simulation device for users' free walking. Using the heuristic evaluation method, a set of items is subjectively assessed: collision and presence feelings within the VE, haptics fatigue and motion simulator sickness. The results showed the application approach validity, but also the need to improve the algorithms for collision detection and physics modeling.

In (Pontonnier, 2014) is presented the evaluation of a virtual prototyping assembly in different environments: real, virtual and virtual with force feedback. The purpose was to determine how to design an assembly for virtual simulations in order to obtain relevant data for a comparison with real assembly tasks. The evaluation is a subjective one, based on the same set of questions for each environment. The results showed that, globally, the virtual force feedback environment is less realistic than the other two environments. This indicates that there is a strong necessity to find innovative solutions for enhancing the users' immersion sensation.

Concluding, the literature analysis showed that, in case of haptic assembly applications, performance is, in general, evaluated by considering one or more of the following metrics: task completion time, error rate per attempt, error rate per task and overall error rate per session. Questionnaires are used to evaluate the users' satisfaction when using the application: cognitive load during use, usefulness of visual and haptic cues, ease of use, application graphics etc.

Two more general observations can be made:

1. Despite the advantages, proven by tests, of using haptic feedback when performing A/D virtual operations, none of the developed applications is currently implemented in commercial software or accepted as official add-on by 3D CAD producers.
2. Different algorithms for reducing the computational time for the collision detection were proposed and implemented. However, to the best of our knowledge, this problem is still not yet satisfactory solved.

## 3. Virtual Environment for Real Time Haptic A/D Simulations

The Collaborative Virtual Environment (CVE), developed by the G-SCOP Laboratory (France), was used as the core of the developed application. This software can manage the interaction between the virtual scene and human through a stereoscopic display and a haptic device. CVE is basically an event propagator between several clients (modules) (Figure 3).

The clients can be executed on the same computer or on several ones through network connection. Every client is in charge of its own task and it does not matter what it is executed by the other clients. It just publishes a shared model which refers, in a more or less complex organization, to a set of concepts that can be evaluated by attributes. Whenever this model is changed, the client is in charge to update a local device, and simultaneously, whenever a local device is activated by the user, its new states values must be propagated to any other interested client.

CVE contains several modules, but for the current application only the following ones were used:

- Stereoscopic display viewer (CVE Viewer): It is a standard 3D viewer which maps VRML, OBJ, STL files in a virtual scene. It can be operated in stereoscopy and thus it acts as the main visual controller.
- Haptic arm (CVE.Haption): The haptic arm device is controlled by a specific client through the states value defining the transformation matrix of the handle and a feedback torsor that returns the efforts that the user must fill.
- Mechanical behavior manager (CVE.ODE): A mechanical scene simulator was build using the Object Dynamic.
- Engine (ODE). On the top of ODE (Smith, 2014), the client creates a mechanical scene which support different functions like: contact detection, kinematic guidance, etc.
- Recorder (CVE.Recorder): The client traces different parameters of the tests: duration, stability of the movement and quality of the final position of a part with respect to an expected target.
- Editor (CVE.Editor): Before launching the tests, a scene editor is used to configure the virtual scene. Later, if needed, the client

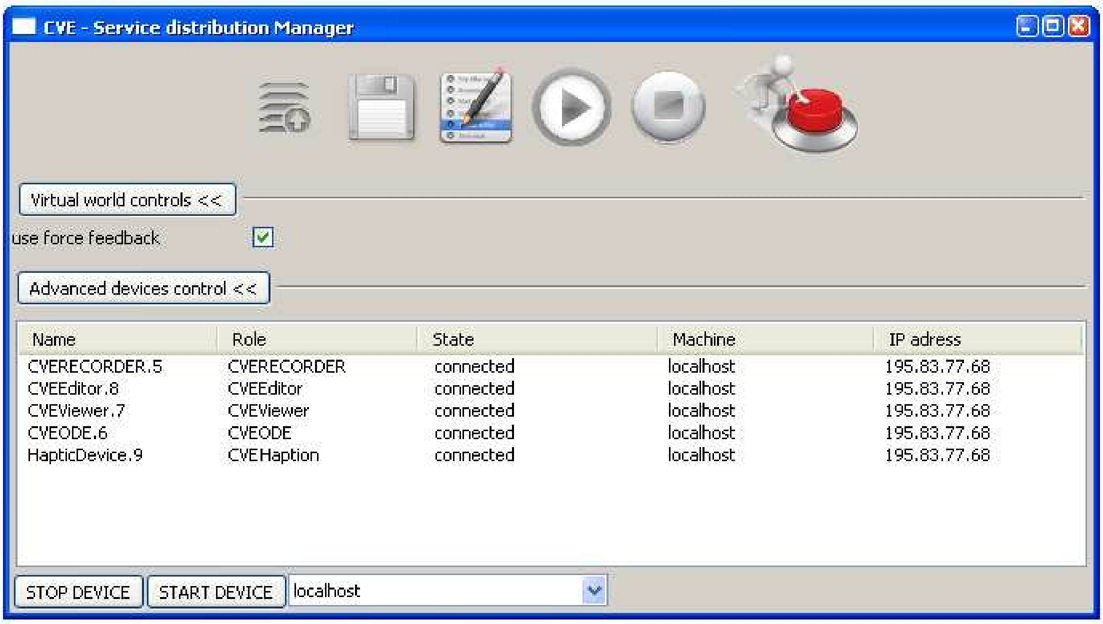


**Figure 3.** CVE main window

can be used to modify different parameters of the simulation environment.

The complete hardware and software elements used for developing the application and for testing are briefly presented in Table 1.

**Table1.** Hardware and software used for CVE

| | |
|---|---|
| Hard | Haptics: Virtuose 6D 35-45 device and arm dedicated controller<br>Stereoscopy: Christie video projector and 3D active glasses<br>Computer: Dell i3 for visualization and haptic rendering |
| Soft | Language: Python 2.7.x<br>Visualization: VTK 5.6.x<br>Collisions: Object Dynamic Engine |

As previously mentioned in Chapter 2, despite the vast amount of research related to the VEs for A/D simulation, there are several unsolved issues. Among these issues, the most difficult one is the simulation, using haptic devices, of detailed A/D operations such as the insertion (extraction) phase of a component into (from) an assembly. Despite the fact that real-time simulation platforms have evolved tremendously, the final element which could render the simulation closer to reality, thus increasing the immersive degree perceived by the user, it is still unavailable. In this context, CVE aims to offer a new type of simulation environment. The main innovation, besides the open application structure, is the implementation of a mobility software module. This one is dedicated to the modeling of contact relationship between elementary components of a product and it is responsible for managing, in real-time, the relative mobilities of the assembly components.

This module can efficiently contribute to the simulation process performed using haptic devices, by by-passing the complex collision detection algorithms and their unrealistic effects when caught with multiple contacts.

This way, A/D operations can be naturally simulated in real-time.

The proposed module has two action levels:

- The first one takes place during the Model Preparation Stage (MPS), as an off-line process, and produces the information used during the insertion/extraction phases of components. Starting with the initial 3D CAD assembly model of a product, an automated identification of the contacts between parts is performed. Using an extended algorithm, the information related to each contact: geometric constraints, contact surfaces relative position, common area etc. is automatically computed and stored in a dedicated data structure. A first implementation was presented în (Iacob, 2013).
- The second one is performed during the Real-Time Manipulation (RTM) of components when they collide with each other. Thus, it can interact with the kinematic models used by haptic arms because the contact type and the nature of the surfaces involved in a contact can help characterizing the nature and the kinematic parameters between two components in contact. This is a complement to the geometric location of contacts, expressing the effective relative movements (the mobility domain) between neighboring components.

In the tested version, CVE can detect and manage in real-time four types of joints (links): Anchorage (ANC - ENC), Planar Fit (PLF - APP), Cylindrical Joint (CLJ - PVG) and Spherical Fit (SPF - RTL). The first joint is a special type and it describes a fixed component in space, as is the case in a real assembly operation. The following three types of joints are standard, defined by functional surfaces of the same type: Planar Fit is formed by two or more planar surfaces, Cylindrical Joint is defined by two or more cylindrical surfaces and Spherical Fit is formed by two or more spherical surfaces. For the moment, a general contact type can be defined and, in the near future, other type of contacts will be included in the algorithm.

CVE can handle the components' movement through a real-time management of collision detection and kinematically constraint guidance.

A simple typical assembly situation is represented in Figure 4, the colour code being the following:

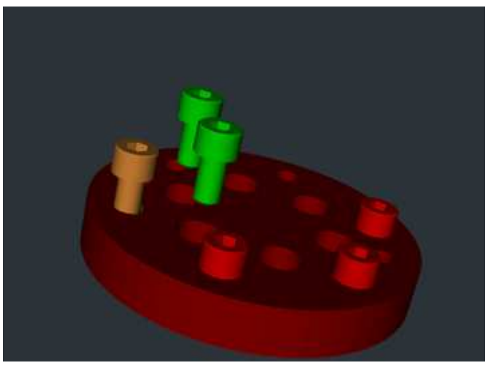

**Figure 4.** A simple assembly situation in CVE

- Red - the component is fixed and it cannot be moved;
- Green - the component can be moved or oriented freely in space;
- Orange - the component has reached a particular position in space where it can be assembled using a constraint guidance;
- Blue - a subassembly constructed from the code using the CVE.Editor module (supplementary, for particular test cases).

The Human Machine Interface (HMI) side was carried out by a 6 DoFs Virtuose haptic arm (Figure 5) with the following interaction functions implemented (Figure 6):

**Figure 5.** Haption Virtuose haptic arm

- Button b.1 - click on part to select/unselect the part or click elsewhere in the scene to manipulate the view (rotation, zoom);
- Button b.2 - click and maintain to reposition the haptic device without changing the scene.
- Button b.3 - no function attached;
- Button b.4 - switched on left side for the right-handed users and vice versa.

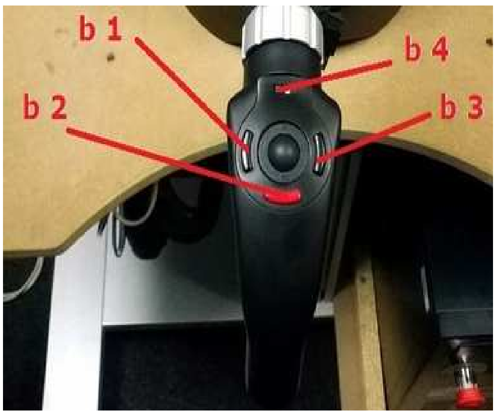


**Figure 6.** Virtuose effector action buttons

## 4. Methodology and Experiments

The main purpose of this research is to evaluate the feedback of a group of users when using the application in integration with Virtuose haptic device. Thus, the following section presents the protocol used, the experimental tasks performed and their results.

### 4.1. Test protocol description

The experiment was built around two tasks that aimed at different purposes.

In the first task, participants were asked to mount 6 screws in 14 holes of a mounting flange. Its main purpose was to familiarize the test subjects with the VE interface and to allow them to practice the basics gesture for models' manipulation.

- 1st assembly task: mounting flange (Figure 4):
  - Type of assembly: simple
  - Number of components: 7
  - Number of interfaces: 12
  - Purpose: becoming accustomed with tasks.

In the second task, participants were asked to mount all the parts of a standard vise assembly.

The complexity of this assembly was increased in comparison with the previous one:

- 2nd assembly task: standard vise (figure 7):
  - Type of assembly: medium
  - Number of components: 16
  - Number of interfaces: 41
  - Purpose: testing/evaluating application.

There was no recommended sequence for mounting the assembly. However, it is important to mention that, in order to obtain the complete assembly, users had first to form subassemblies.

An exploded view of the assembly was provided to all participants in order to facilitate the understanding of the assembly scheme. The light was dimmed in the room for allowing reading papers, while not reducing the visibility of the stereoscopic view of the assembly operations.

The testing phase included three steps with a total time of 45 minutes:

- Planning: initial discussion for presenting the application and experiments, filling in the pre-questionnaire;

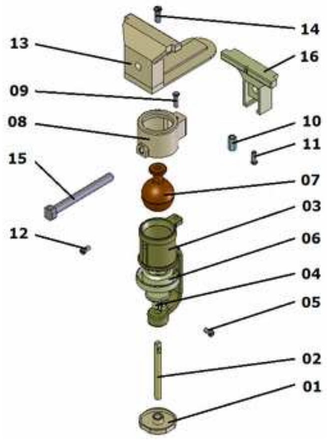


**Figure 7.** Standard vise assembly

- Performing experiments (task 1– flange and task 2 – vise) – objective assessment;
- Applying questionnaires –subjective assessment.

For this experiment, 20 candidates (18 men and 2 women) were chosen from a group of people with engineering background (master and PhD students, professors and researchers). The group's average age was 35.

### 4.2. Data collection

Objective and subjective evaluations have been made as follows:

- Quantification of parameters measured in real-time through the software. The test session was recorded and two types of parameters were measured in real-time:
- Number of assembled components;
- Average time for a component assembly.
- Questionnaires. A standard Likert scale (1 – absolutely not to 5 – absolutely yes) was used. Some of the questions were asked at the beginning of the experiments and had the purpose to characterize the participants' group. Thus, 80% of participants were 3D CAD users, 60% of them previously experienced stereoscopic view and 80% of them previously used haptic devices.

The other questions provided information on users' satisfaction related to application's ease of use, usefulness of stereoscopic view, utility of the haptic cues. These questions were asked after performing the assembly tasks:

- Q1. The interaction is natural in the virtual environment.
- Q2. You had good control over the parts.
- Q3. It was easy to perform the application tasks.
- Q4. The software functions are well defined and programmed.
- Q5. The application graphics is accurate enough for performing the assembly operations.
- Q6. The haptic feedback is a useful dimension of the application compared to standard input devices (e.g. basic mouse, 3D mouse, joystick).
- Q7. The application could be useful for the design stage.
- Q8. The application could be useful for training in the field.
- Q9. The application could be useful for ergonomics evaluation.
- Q10. The application could be useful for maintenance evaluation.

## 5. Results and Discussions

Figure 8 presents a chart of the real-time measured parameters for the second assembly

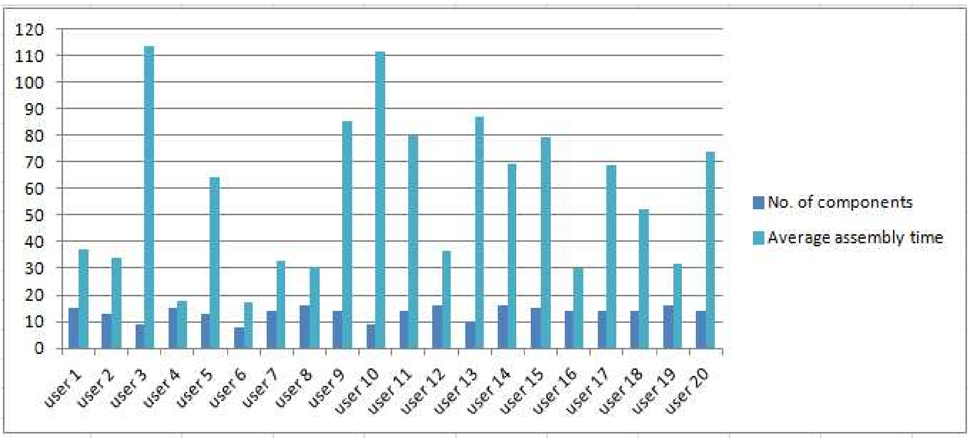


**Figure 8.** Results for real-time measured parameters

task (task 2): number of components and corresponding average assembly time for each user. The results showed that all participants assembled a minimum number of 8 components in a maximum time of 114s.

Moreover, 16 participants assembled more than 13 components in an average time of approximately 52s.

The medium number of assembled components in scenario 2 is 13 (of 16 components, percentage > 80%) in an average time of 58s. This, corroborated with users' questionnaires answers and final discussions, proves that the developed application is ease to learn and use.

Three participants assembled all components in an average time of 46s, and one participant finished the task in 32s. In his performance, a significant previous experience in using high quality haptic devices played an important role.

One observation should be mentioned regarding task 2. In order to fully assemble the vise, users had to form a sub-assembly of 12 parts, then to make a second sub-assembly of 4 parts and, finally, to assemble these two sub-assemblies. Although the application allows component dismounting, the users were not allowed to disassemble parts in case they wrongly placed a component, considering that there was clear information on the assembly sequences. This can explain the results recorded by user 6, for instance, who assembled 8 parts in139s, and then stopped because of wrongly placing parts.

Another mention should be made related to user 10. He has a lot of practical experience in manually building assembly and manufacturing parts, but this did not determine an equally high performance in the VE.

Table 2 presents the participants' answers at questions. The analysis of this set of answers offers a global view of users' opinion related to the items described above.

Figure 9 presents the answers' distribution corresponding to each value on the Likert scale (1 – absolutely not to 5 – absolutely yes).

**Table 2.** Questionnaires results – Likert Scale

| User Q | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** | **Mean** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Q1** | 2 | 4 | 2 | 4 | 2 | 2 | 4 | 4 | 4 | 5 | 3 | 3 | 3 | 3 | 3 | 4 | 3 | 5 | 4 | 3 | 3,35 |
| **Q2** | 4 | 5 | 3 | 4 | 2 | 4 | 3 | 4 | 5 | 5 | 4 | 3 | 3 | 3 | 2 | 5 | 4 | 5 | 4 | 3 | 3,75 |
| **Q3** | 4 | 5 | 2 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 2 | 3 | 3 | 4 | 3 | 4 | 3 | 4 | 4 | 3 | 3,65 |
| **Q4** | 3 | 4 | 4 | 4 | 3 | 3 | 4 | 4 | 4 | 4 | 3 | 4 | 4 | 4 | 3 | 4 | 4 | 4 | 4 | 3 | 3,7 |
| **Q5** | 5 | 4 | 4 | 5 | 5 | 5 | 5 | 4 | 5 | 3 | 4 | 5 | 4 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 4,2 |
| **Q6** | 5 | 4 | 3 | 4 | 2 | 5 | 3 | 4 | 5 | 4 | 2 | 2 | 4 | 4 | 3 | 3 | 5 | 4 | 4 | 4 | 3,7 |
| **Q7** | 5 | 3 | 4 | 2 | 3 | 5 | 4 | 3 | 5 | 4 | 4 | 4 | 3 | 4 | 4 | 3 | 3 | 4 | 4 | 4 | 3,75 |
| **Q8** | 5 | 3 | 3 | 4 | 4 | 5 | 4 | 2 | 4 | 3 | 5 | 5 | 5 | 5 | 4 | 4 | 5 | 4 | 4 | 4 | 4,1 |
| **Q9** | 2 | 5 | 4 | 3 | 2 | 2 | 4 | 2 | 4 | 3 | 4 | 3 | 5 | 2 | 4 | 2 | 5 | 5 | 4 | 4 | 3,45 |
| **Q10** | 4 | 4 | 3 | 4 | 4 | 4 | 3 | 3 | 4 | 3 | 3 | 4 | 4 | 2 | 5 | 4 | 3 | 5 | 4 | 4 | 3,7 |

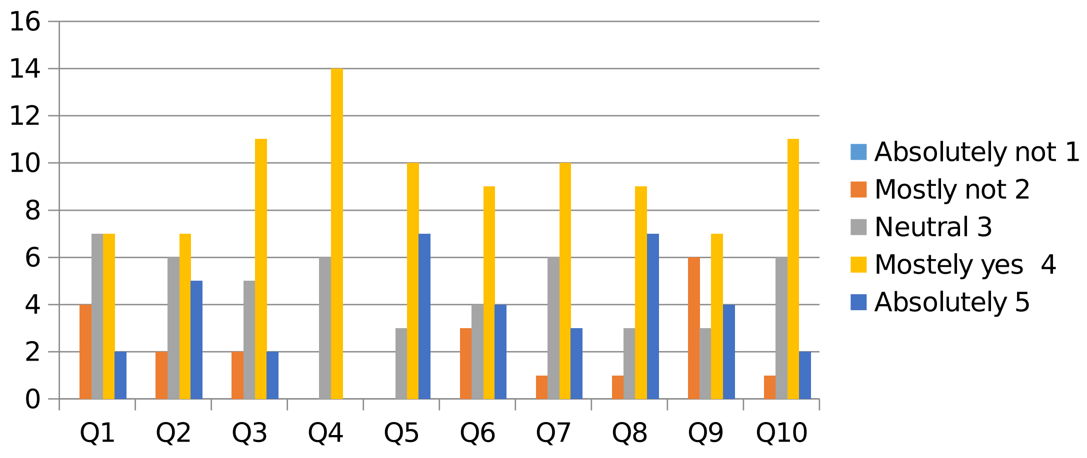


**Figure 9.** Answers' distribution for each question

Mainly, the following conclusions can be enumerated from the questionnaires' analysis:

- Application was perceived as useful, the functions well defined and the 3D graphics accurate enough for performing the tasks;
- Users were able to fully assembly, without difficulties, all the components using the kinematic guidance algorithm;
- Problems were mentioned in some configurations, when the collision detection was used – algorithm that should be improved.

## 6. Conclusions

Haptic feedback is an important element for the A/D process immersive simulation. Despite this, the technology is still under-represented in the everyday computer interface, mainly because of two reasons: the commercially available haptic devices are still relatively expensive, and the existing A/D immersive software is not offering robust functions for real-time simulations.

In this context, the main objective of the current research was to evaluate a new immersive simulation application based on component real-time mobility management. The evaluation was performed by a group of 20 participants using several tests for assessing the following criteria: usefulness, efficiency, ease of use, quality of the haptic feedback and overall impression.

Subjective and objective evaluations were made, the overall results and opinions showing the feasibility of the proposed approach.

Thus, several conclusions were drawn:

- The application was considered useful and easy to use, but the collision detection algorithm should be improved.
- Due to the implementation of the kinematic guidance algorithm, all the components can be completely assembled in a natural way. This represents an innovative solution to a major limit of existing VEs.
- Different types of feedback should be offered, depending on the simulation objectives, thereby increasing the user immersion sensation.
- Further work will address the implementation of a new collision detection method in order to solve some problems regarding the haptic feedback with which users confronted during experiments.
- Using a different investigation procedure, other extensive studies will be performed for assessing intra-users variations.

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## REFERENCES

1. BORDEGONI, M., CUGINI, U., BELLUCO, P., ALIVERTI, M., **Evaluation of a Haptic-based Interaction System for Virtual Manual Assembly,** Lecture Notes in Computer Science, vol. 5622, 2009, pp. 303-312.
2. DEBEVEC M., SIMIC M., HERAKOVIC N., **Virtual Factory as an Advanced Approach for Production Process Optimization**, International Journal of Simulation Modelling, vol. 13, no. 1, 2014, pp. 66-78.
3. GONZALEZ-BADILLO, G., MEDELLIN -CASTILLO, H., LIM, T., RITCHIE, J. M., SUNG, R., GARBAYA, S., **A New Methodology to Evaluate the Performance of Physics Simulation Engines in Haptic Virtual Assembly**, Assembly Automation, vol. 34, no. 2, 2014, pp. 128-140.
4. GONZALEZ-BADILLO, G., MEDELLIN -CASTILLO, H., LIM, T., RITCHIE, J. M., GARBAYA, S., **The Development of a Physics and Constraint-based Haptic Virtual Assembly System**, Assembly Automation, vol. 34(1), 2014, pp. 41-55.
5. IACOB, R., POPESCU, D**., Generation of Disassembly Directions based on Component Mobility**, Studies in Informatics and Control, vol. 22, no. 4, 2013, pp. 307-318.
6. KHAN, M., SULAIMAN, S., TAHIR, M., SAID, A. M., **A study on usability factors for haptic systems**, International Journal

of Computer Theory and Engineering, vol.5, no. 3, 2013, pp. 500-502.

7. LIM, T., RITCHIE, J. M., DEWAR, R. G., CORNEY, J. R., WILKINSON, P., CALIS, M., DESMULLIEZ, M., FANG, J. J., **Factors affecting user performance in haptic assembly**, Virtual Reality, vol. 11, no. 4, 2007, pp. 241-252.

8. PONTONNIER, C., DUMONT, G., SAMANI, A., MADELEINE, P., BADAWI, M., **Designing and evaluating a workstation in real and virtual environment: Toward virtual reality based ergonomic design sessions**, Journal on Multimodal User Interfaces, December, vol. 8, no. 2, 2014, pp.199-208.

9. PUPAZA, C., CONSTANTIN, G., NEGRILA, S., **Computer Aided Engineering of industrial robots**, Proceedings in Manufacturing Systems, vol. 9, no. 2, 2014, pp. 87-92.

10. SAMUR, E., WANG, F., SPAELTER, U., BLEULER, H., **Generic and Systematic Evaluation of Haptic Interfaces based on Testbeds**, Proceedings of ICIRS, 2007, pp. 2113-2119.

11. SETH, A., SU, H.J., VANCE, J. M., **SHARP: a system for haptic assembly and realistic prototyping**, Conference ASME – DETC, Philadelphia, September 2006, pp. 1-8.

12. SETH, A., VANCE, J. M., OLIVER, J. H., **Combining dynamic modeling with geometric constraint management to support low clearance virtual manual assembly**, Journal of Mechanical Design, vol. 132, no. 8, 2010, pp. 1-7.

13. SMITH, R., **Open Dynamics Engine library**, http://ode-wiki.org/wiki/index.php, 2014.

14. THORSTEINSSON, G., PAGE, T., NICULESCU, A., **Using virtual reality for developing design communication**, Journal of Studies in Information and Control, vol. 19, no. 1, 2010, pp. 93-106

15. XIA, P., LOPES, A.M., RESTIVO, M. T., YAO Y., **A new type haptics-based virtual environment system for assembly training of complex products**, Intlernational Journal of Advanced Manufacturing Technology, vol. 58, no. 1, 2012, pp. 379-396.