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Effect of weight perception on human performance in a haptic-enabled virtual assembly platform

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Abstract. Virtual assembly platforms (VAPs) provide a means to interrogate product form, fit and function thereby shortening the design cycle time and improving product manufacturability while reducing assembly cost. VAPs lend themselves to training and can be used as offline programmable interfaces for planning and automation. Haptic devices are increasingly being chosen as the mode of interaction for VAPs over conventional glove-based and 3D-mice, the key benefit being the kinaesthetic feedback users receive while performing virtual assembly tasks in 2D/3D space leading to a virtual world closer to the real world. However, the challenge in recent years is to understand and evaluate the added-value of haptics. This paper reports on a haptic enabled VAP with a view to questioning the awareness of the environment and associated assembly tasks. The objective is to evaluate and compare human performance during virtual assembly and real-world assembly, and to identify conditions that may affect the performance of virtual assembly tasks. In particular, the effect of weight perception on virtual assembly tasks is investigated.

Keywords: virtual assembly platforms; haptics; assembly task; weight perception.

1. Introduction

According to Howard and Vance [1], a successful virtual assembly environment requires virtual parts to emulate real parts in real world. Two basic methods for simulating physical part behaviour are physically based modelling (PBM) and constraint based modelling. PBM uses Newtonian physics laws to describe the motion of objects and forces acting on bodies and to model realistic behavior by simulating the effect of gravity and collision response between objects in the virtual environment.

Several VR platforms for mechanical assembly have been developed over the years. From these developments, it has been observed that the time required to complete a virtual assembly task is always larger than the time required for the same assembly task in the real world. Several factors that may contribute to this difference include: the interface used (haptic device, glove, 3D mouse, etc), the manipulability of virtual objects, virtual objects shape and weight, camera manipulation, rendering type (stereo-view, 2D screen, head mounted displays), force feedback, etc.

In this paper the influence of weight of virtual objects in virtual assembly task is investigated in order to identify their effect on the completion time of virtual assembly tasks. The investigation is carried out using a virtual PBM assembly platform enabled with haptics.

2. Related work

During the last decade several researchers have proposed different types of virtual assembly environments with some interesting conclusions. Wang et al. [2] analysed methods of dynamic simulation that may affect the assembly task. A scaling factor for gravity was used, which was attained by trial and error. It was concluded that dynamic simulation of parts in virtual environments greatly enhances the realistic feelings of virtual spaces but does not contribute significantly to the assembly task.

On the other hand, Lim et al. [3, 4] investigated the impact of haptic environment on user efficiency while carrying out assembly tasks. It was observed that small changes in shape, the use of full collision detection and the use of stereo-view, can affect assembly times in haptic virtual assembly environments, Similar results were obtained by Garbaya [5], who observed that human operators have superior performance when provided with the sensation of forces generated by the contact between parts during the assembly process.

Huang [6] studied the effects of haptic feedback on user performance when carrying out a dynamic task using a beam and ball experiments. The results showed that user performance is affected by the magnitude of the force feedback and the complexity of the system dynamics.

The problems related to haptic interaction between human operator and virtual environments were investigated by Tzafestas [7]. The results demonstrated that human perception of weight when manipulating objects in virtual environments is similar to the pereception when manipulating real objects. It was also concluded that imperfections and limitations of the mechatronic haptic feedback device may lead to a small decrement on the user performance.

The influence of control/display ratio (C/D) on weigth perception of virtual objects was evaluated by Dominjon [8]. The results showed that when using a C/D ratio smaller than 1, amplification of user movements on virtual environment, the participants perceived the manipulated object ligther than its actual weight, in some cases it was even possible to reverse weight sensation to make a heavy object feel lighter than a light object. This suggested that mass can be added to the list of haptic properties that can be simulated with pseudo-haptic feedback.

Hara [9] examined user weight perception when the heaviness of a virtual object suddenly changes using a haptic device, results indicate that users perceive a change in weight of the virtual object only when the difference between the initial and the actual weight is significative, it was concluded that when the user cannot perceive the change of weight, he/she may unconsciously adjust their muscle command to the weight change.

Uni-manual and bi-manual weight perception when lifting virtual boxes was evaluated by Giachristis [10], who proposed that accurate perception of simulated weight should allow the user to execute the task with high precision.The results indicated that bi-manually lifted virtual objects tended to feel lighter than the same objects unimanually lifted. Users seem to be five times less sensitive to virtual weight discrimination than for real weights.

Vo and Vance [11] examined the context in which haptic feedback affects user performance. In the weight discrimination task the user was asked to idendify the heaviest object of a couple of virtual models showed. The results obtained showed that users compared models in less time using haptic feedback than using only visual perception and that identification of weight is dependent on which hand was used to manipulate the object.

According to the previous research works, a method to evaluate user performance in virtual assembly tasks is by measuring the Task Completion Time (TCT). Several authors have observed that the weight of virtual objects is one of the most important factors that affect the TCT [7, 8, 9]. Thus, this work evaluates the effect of virtual weight on the TCT. An assembly task is used as case of study to compare the performance of virtual assembly vs. the real assembly in terms of the TCT.

3. System overview

A haptic virtual assembly system, named as HAMMS, has been developed and it is shown in Fig. 1. The HAMMS interface has been developed in Visual C++ and comprises the Visualization Toolkit libraries (VTK 5.8.0) and the Open Haptics Toolkit v3.0. Two physics engines, PhysX™ v2.8.4 and Bullet v2.79, have been integrated in HAMMS and the user is able to select any of them during run time. Single and dual haptic is provided using Sensable's Omni haptic device. One of the main characteristics of HAMMS is a control panel where the user can modify in real time simulation parameters; haptic properties like stiffnes, damping and friction; and physical properties like mass, restitution, tolerance, etc.

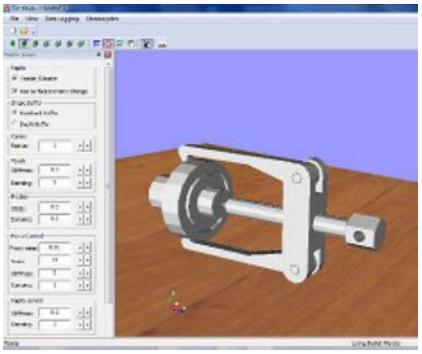


Fig. 1. HAMMS interface

The use of chronocycles [12] is also implemented in the HAMMS platform, allowing the user to graphically observe the path of the assembly once it is completed.

Two interaction phases are identified while the application is running: the first logs when the objects are only touched ("inspect") by the haptic proxy but not manipulated, the second phase is when the objects are being manipulated ("control") with the haptic device. In the "control" phase the physics model is attached to the haptic model by a spring – damper system and the graphic model is updated with the physic model (Fig. 2).

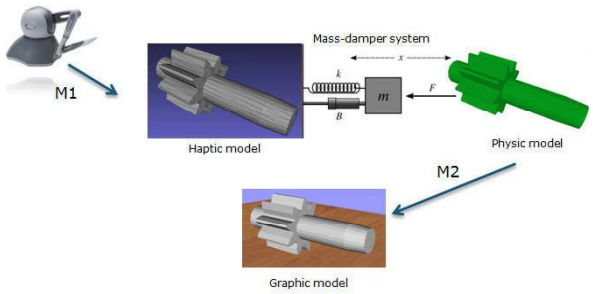


Fig. 2. "Control" phase of virtual objects

The use of the spring-damper model allows the calculation of force feedback that the user will feel when a collision occurs or when virtual objects are manipulated (weight perception). The values of spring constant and damping are determined empirically and adjusted so that smooth and stable movement of the manipulated part is obtained [5].

4. Experimental setup

The assembly task selected in this investigation was a gear oil pump. The pump comprises five parts: the

housing, a big cog, a small cog and two figure-eight bearings retainers. The virtual and real pump components are shown Fig. 3. The virtual objects are imported into the HAMMS application as STL files.

(a) (b)

Fig. 3. Pump components, a) Virtual and b) real

Eight levels of weight, measured in Newtons (N), are defined for each pump component, L1 to L8, where L1 is the minimum weight and L8 the maximum weight in the virtual scene. The virtual and real weights are presented in Table 1. These virtual weights were obtained by scaling the density of the virtual objects. The maximum force suported by the Sensable Omni Device (3.3 N) was considered when assigning the weight level 8 to the heaviest manipulated object, the big cog. The housing is not considered because during the assembly process, real and virtual, it is the base part and remains static.

The real assembly was performed by 5 persons with each subject performing the task with one and two hands. The virtual tasks were carried out by an experienced user in both haptics and virtual assembly in order to avoid learning. The pump assembly was performed four times for each level of weight and using one and two hands. The virtual assembly tasks were performed using both physics engines, Bullet Physics and PhysX^{tm}, in order to observe the influence of different simulation engines on the assembly process.

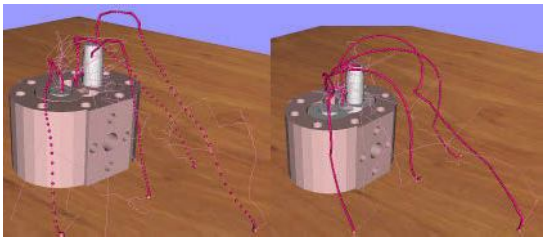
Table 1. Levels and weights (N) of pump components

Level	Housing	Big Cog	Small cog	Bearings
L1	0.02	0.02	0.02	0.02
L2	1.3	0.17	0.13	0.1
L3	3.34	0.41	0.34	0.29
L4	>4	0.82	0.66	0.51
L5	>4	1.11	0.9	0.69
L6	>4	1.64	1.31	1.01
L7	>4	2.23	1.81	1.34
L8	>4	3.24	2.71	1.47
Real	16.7	6.7	5.2	1.6

5. Results and discussion

The chronocycles employed in HAMMS offer a graphic representation of the trajectories and user haptic manipulations in the virtual environment. When a virtual object is being manipulated with the haptic device the movements are recorded and once the assembly has been completed chronocycles can be observed to analyse the manipulation of the object. Figs. 4 (a) and (b) show the chronocycles of the pump assembly task using level of weight L1and L8 respectively. The red spheres represent the path of the virtual objects when they were manipulated by the haptic device, and the distance between each sphere represents the speed of the motion; a low velocity is identified when one sphere is very close to the next one.

From observation, the initial manipulation of the object, when moving from its initial position to the target position, is faster at weight level L1 compared to level L8. This is verified from the chronocycles curves for L8, suggesting that larger inertia influences the assembly operations. With increased inertia in the virtual objects, the manipulation speed decreases, as it occurs in the real world, i.e. heavier objects are more difficult to manipulate.



(a) (b)

Fig. 4. Chronocycles using A) weight L1, B) weight L8

The task completion time in Fig. 5 shows the results obtained from a single-handed assembly task. In the case of the real assembly task, the TCT mean value for one hand was 37 seconds. The TCT of the virtual assembly task using the PhysX simulation engine is shown as the red dashed line, while the same virtual task but using Bullet physics is shown as the green dotted line. Both red and green lines represent the mean values for each level of weight.

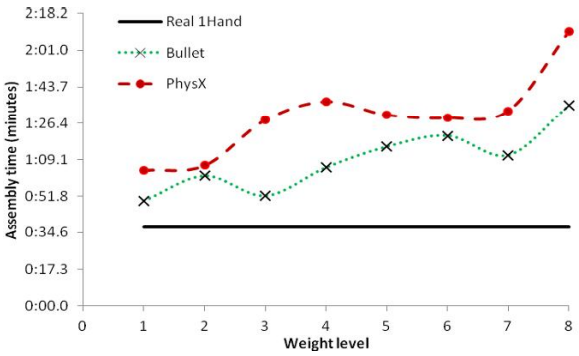


Fig. 5. Task completion time with one hand

From the results (Fig. 5) the minimum assembly time when using one hand corresponds to the weight level L1, where the weight of virtual components is minimal (0.02 N), only enough to keep the system stable. Using Bullet physics the minimum mean time was 49 seconds, with minimum TCT reported at 39 seconds. For PhysX the minimum mean value was 64 seconds and the minimal reported value was 59 seconds. The mean value for the task completion time (TCT) for one hand real assembly was 37 seconds and for two hands 27 seconds.

Figure 6 shows the results obtained with bi-manual assembly. The real process took an average of 27 seconds to complete. In the virtual experiments with two hands the minimum TCT value also corresponded to weight level, L1. Bullet physics posted a minimum mean time of 52 seconds, with a minimum reported assembly time of 44 seconds. In the case of PhysX, the TCT for weight level L1 was 75 seconds and the minimum reported TCT 61 seconds. A dip can be observed in weight level L6 for both simulation engines, Bullet and PhysX, this may be due to compensation of haptic stiffness; at weight level L6, the weight of all the models are above 0.88 N, that is the maximum continuous force for the Phantom Omni device; this value must not be confused with the maximum rendering force.

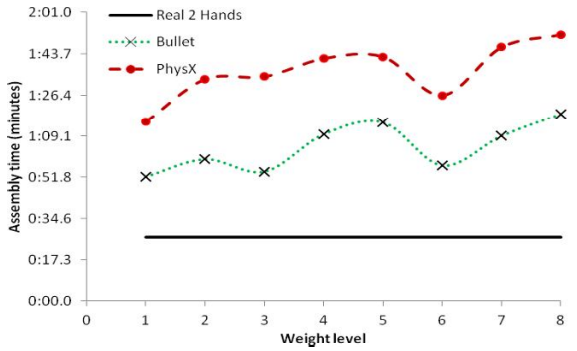


Fig. 6. Task completion time with two hands

The procedure to assemble the pump using two hands in the real world was very similar to the assembly in the virtual environment; two hands were used to align and fit the gears in the housing and bottom bearing. In the real assembly process, the TCT was smaller when using two hands than when using only one hand, however in the virtual environment the TCT using two haptic devices was greater than when using only one device. This difference may be caused by the collision response, such as sticky objects or unnatural reactions, when two objects are being manipulated. It was also observed that the fitting and aligning of the two gears was a difficult task in the virtual environment when using two hands. In general, it was observed that the time to complete a real assembly task is still smaller than the time to complete the same assembly task but in a virtual environment. Weight perception affects the TCT, as the weight of the virtual objects increases, the assembly time increases. Also, it can be said that the physics engine affects the performance of the assembly task.

6. Conclusions and future work

The effect of weight perception on human performance in virtual assembly environments enabled with haptics has been investigated. The results suggested that the performance of virtual assembly tasks, in particular the TCT, is directly affected by the weight of virtual objects; i.e. as the weight of virtual objects increases, the TCT will also increase. The chronocycles analysis showed that as the weight of the manipulated objects increases, the manipulation velocity decreases. Further investigation considers the analysis of the weight perception effect on the user by measuring muscle and brain activity in order to identify how the user reacts to different conditions on virtual assembly tasks.

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