Thesis progress report

Thesis Title: Sensorimotor Interface for Collaborative Virtual Environment based on heterogeneous interactive device: Application to Industrial Design

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Thesis Subject

Virtual Reality (VR) technology reduced the time and cost in Product Lifecycle Management (PLM) thanks to realistic digital mockup. All actors, from engineers to end users can interact with the virtual mockup from an early design stage as a substitute of costly physical prototypes.

However, these VR techniques has not yet fully improved early design activity. Due to the complexity of a data model, it is hard to integrate any Computer Aided Design (CAD) software into a VR design space [1]. An integrated VR-CAD design platform could provide the common work space for industrial designers, CAD engineers and/or end-users, using an immersive visualization and intuitive interactions. In particular, a 3D interaction in an immersive environment might simplify the manipulation of complex CAD user interface: according to the field study in the automotive industries, the cost of CAD training is about 10-16 man-years, around 5% of resource costs per year [2].

In addition, a VR-CAD design platform should be able to adapt to any VR system based on user’s preference, since various VR devices are now available with the rapid development of the technology.

The goal of this thesis is to build and test a collaborative CAD design system between heterogeneous VR platforms. As a proof of concept, this thesis project use two immersive platforms in Saclay: a CAVE-like system (EVE system, Venise group - CNRS/LIMSI) and Wall-sized display (WILDER, ExSitu group - LRI/INRIA), thus our VR-CAD system is investigated across these facilities.

In order to investigate this subject, our main focus points (FP) are as following:

FP1. CAD design activity in VR platform
FP2. 3D interaction for design and modification of CAD objects
FP3. Collaborative design from heterogeneous VR platforms
Current Work

Currently, we have been mainly studied for FP1 and FP2 in past two years. A previous Ph.D student, Pierre Martin (Venise group, LIMSI/CNRS), had been working for FP1, and developed a conceptual VR-CAD system, cReaRV. Our first attempt was to refine cReaRV and investigate a 3D interaction technique for intuitive CAD-data modification (FP2). For a precise 3D manipulation, we implemented a new interaction technique using a force feedback device and evaluated its efficiency though user studies.

This report describes our studies of VR-CAD system, 3D interaction technique and my future perspectives.

1. VR-CAD system

1.1. Background
Various research projects have been conducted to allow interaction with CAD data from a VR platform to enhance user interaction and object perception. However, VR-CAD data integration still suffer from data interoperability between VR and CAD system. For example, most existing immersive project review system are using a dead model (data generated after tessellation of the CAD data into a 3D mesh) which does not contain semantic information, such as Constructive History Graph (CHG) or also called design history graph. CHG stores the information of design history of CAD object: operators, parameters, transformation matrices, etc.

Without any direct access to original CAD data, users have to back and forth the immersive platform and workstation to apply their modifications. Some works can access to CAD data and modify it in virtual environment [3][4], but nevertheless, they cannot reflect their modification onto original CAD file.

1.2. cReaRV
cReaRV was developed to retain CHG of CAD object in VR session and directly modify the parameter values from relevant shapes [15]. The base concept of cReaRV is a labeling [6]: a direct linkage between VR rendering of the Boundary Representation (B-Rep) of a CAD object with the nodes of CHG. Pierre Martin extended this model with an encapsulation technique to apply this method onto most CAD systems used by industry. A proof of concept was implemented over CATIA V5® (Dassault Systémes), which allowed users to implicitly access to the parameter values of the CHG nodes which are relevant to modify the shape of a B-Rep element (Fig.1). With cReaRV, users can directly modify the features of native CAD shapes during VR session.

1.3. Parametric modification in cReaRV
Users can manipulate the specific parameter value with scrolling interaction after the selection of a part. We implemented cReaRV [5] on CAVE-like system,
composed of 4 screens (Left, right, front and floor), and users can increase/decrease the parameter value with hand motion to the right/left while handling a motion captured Wiimote controller (Fig.2). As a target CAD mode, we used an actual Rear-view mirror created by an industrial designer from an automotive company. This Rear-view mirror is described in detail at Fig. 7. Fig.3 shows the interaction flow of cReaRV.

Fig.3. Example of cReaRV session. 1) Rear-view mirror designed in CATIA V5. 2) Object exploration. 3) Topological selection. 4) Distance modification. 5) Save/exit. 6) Check of modified CAD object reloaded in CATIA.

1.4. Program refinement

cReaRV could successfully import and export native CAD data for shape deformation in an immersive environment. However, the interaction method was not optimal for manipulation in 3D space: a one dimensional scrolling interaction is as opposed to the three dimensional visualization. Stark [7] pointed out the current problems for merging desktop-CAD and VR, and main issues are “interaction technique of current CAD systems cannot be transferred one-to-one to VR systems” and “the accuracy of modelling operations cannot be assured”.

In order to solve these problems and the instability of the system, I thereby updated whole system architecture of cReaRV. Previously, cReaRV ran all simulations (CAD engine interactor, user interaction and graphic rendering) in one process, so that it was difficult to update each part separately. This was a huge bottleneck to deal with several VR devices and/or platforms. Thus, I firstly designed an external CAD engine interactor (read mesh and CHG data, and request modification) as Wang’s system [16]. Other two processes were also decomposed into independent process, and previous graphic rendering system were replaced by Unity.

The designed system architecture is described in following section. The new system makes it possible to support heterogeneous VR platforms, and also it solved some instability issues of cReaRV.

2. 3D Interaction technique for Parametric CAD data Modification in VR space

2.1. Inconsistent Interaction at parametric CAD deformation

Most VR-CAD applications place value on coherent dimension between visualization and interaction space. According to Clark [8], “To expect a designer of 3-D surfaces to work with 2-D input and viewing devices unnecessarily removes a valuable degree of freedom”. For example, pushing/pulling interaction for object manipulation was introduced in [9], and MockUp Builder [10] applied this interaction for object creation/edition on multi-touch table top display with co-localized manipulation.

1) http://unity3d.com
However, no applications can use such an interaction on parametric CAD objects, especially containing constraints. The main difficulty is that parametric-based modification often causes an “unpredictable” shape deformation, which leads to inconsistent interaction in 3D space.

From interviews with designers and CAD users, Chu [11] defined requirements to design multi-sensory CAD user interfaces and proposed to resize shape using a scroll motion of user’s hand in 3D space. Such interactions are used in many parametric CAD data modifications as cReaRV. However, it should be extended to 3D interaction for allowing non-CAD experts to modify CAD data.

2.2. ShapeGuide

In order to address a numerical manipulation from a 3D interaction, I developed ShapeGuide, a 3D interactive technique based on a set of shapes which guides the user hand motion during CAD object deformation. With this technique, users can modify parametric constraints of CAD objects with direct 3D shape interaction.

The main difficulty of a 3D shape-based interaction at a constraint-based CAD data is the “unpredictability” of the shape modification from a given parameter change.

To anticipate the direction of the shape deformation, I compute several meshes from a set of discrete parameter values with a slight offset from the initial value. In such a way, users can choose one of the proposed shape with 3D hand motion. Only the closest shape from the visual proxy of a hand is rendered in the virtual environment, so that the shape appears to be following user’s hand as a pushing/pulling interaction with the CAD object regardless of its hidden internal topological complexity.

Firstly, I decomposed the architecture of cReaRV into three processes, graphic rendering (VR Platform), CAD engine communicator (VR-CAD Server) and interaction (VHServer), to support heterogeneous VR platform for future use and to perform haptic compliant physic computation (Fig. 4).

When a user select a parameter of a CAD object from a part picking in the virtual environment, the selected part information and an empirically defined parameter evolution are sent to the VR-CAD Server. Then, VR-CAD Server send the expected modification request to CAD engine. After tessellation of the different B-Rep data computed from the parameter set, all generated meshes are saved into a Shared folder. The relationships between B-Reps and CHG, provided by the labeling technique, are also saved in Shared folder with custom XML file (ShapeGuide.xml). Visuo-haptic server (VH server) imports the Meshset in order to compute haptic rendering and transmit the closest mesh ID to a VR Platform to switch the current visualized mesh. Finally, VR Platform loads Meshset and ShapeGuide.xml for visual feedback. Constraint names and parameter information described in ShapeGuide.xml are mapped onto each mesh to allow users to implicitly select these values from surfaces. The virtual environment is simulated by Unity, and MiddleVR for Unity manages the clustering rendering.

2.3. 3D interaction mechanism

ShapeGuide interaction allows to select one of the available meshes within the computed mesh set from a given hand 3D position $P_{\text{hand}}$ (Fig. 5).

2) http://www.middlevr.com/
At each frame, *VH server* computes each nearest point $P_i$ and minimal distance on each mesh of the *Meshset*. Then, two closest points positions $P_{closestA}$ and $P_{closestB}$, and nearest mesh Ids $MeshIdA$ are stored for later force feedback computation. $MeshIdA$ is sent to *VR-CAD Server* immediately to display the selected nearest shape in real time.

### 2.4. Haptic feedback

One of the benefit of *ShapeGuide* is that the force feedback can be integrated on deformation task to enhance the pushing/pulling interaction.

My force feedback model is inspired by Force feedback grid [12]. Force feedback grid can snap user’s hand to the attractive points distributed on the cartesian axis. As a visual proxy comes close to the attractive point, the amount of the force become higher. Yamada explains this force concept as *"This is analogous to the force by which a piece of iron would be attracted to a magnet"*. My force model allows to convert this magnetic guide metaphor from homogeneous cartesian grids to any arbitrary axis in 3D space. The attractive point is on the surface ($P_{closestA}$) which is acquired from the distance computation process. The amount of the magnetic force $F_m$ is described in Fig. 6.

$$F_a(x) = \begin{cases} 
F_{max} \frac{\varepsilon}{x} & x \in [0, \varepsilon] \\
(F_{max} - F_{min}) \cdot \frac{D - \varepsilon}{D - x} + F_{min} & x \in [\varepsilon, D] 
\end{cases}$$

Computed force ($F$) is modulated by the velocity of the user’s hand with dumper model in order to avoid the vibrations nearby $P_{closestA}$.

$$F = F_m - B \cdot \dot{x}$$

### 2.5. Experiment

In order to assess the efficiency of *ShapeGuide* on a CAD deformation task, I conducted a controlled experiment to compare it with a scroll technique, named *Scroll*. I also wanted to assess the effect of an additional magnetic force feedback on both interaction techniques. This magnetic force feedback enables participants to feel the different parameter values during the modification.

For *Scroll*, users can select the parameter values with a horizontal scrolling motion as *cReaRV*. Each parameter step is equally distributed on the horizontal axis, and a visual feedback of the corresponding modified shape is updated during the manipulation. Each point attracts user’s hand in magnetic force feedback condition.

From our assumptions based on the related works and some first pilot tests, I formulate the following hypotheses:

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**Fig.5.** Example of computed MeshSet for the right side part for 3D interaction. $P_{hand}$ is user’s hand position. $P_i$ is a nearest point on each surface from $P_{hand}$.

**Fig.6.** Amount of the attractive force ($F_a(x)$) during selection of a shape. Red arrows describe user’s hand position.
H1. participants achieve the deformation task faster with ShapeGuide than with Scroll.
H2. participants are more likely to start the deformation in the correct direction with ShapeGuide than with Scroll because of the consistency of the gesture with the deformation direction.
H3. ShapeGuide is preferred in comparison to Scroll.
H4. the magnetic force feedback helps participants to reach the desired parameter values with more precision, especially with ShapeGuide.

CAD Object
For this experiment, I used an actual Rear-view mirror created by an industrial designer from an automotive company (Fig. 7).

Users can access to the constraints and parameters of the guide curve by selecting one of the corresponding surface in the virtual environment. For example, when users select a right side part of Rear-view mirror, VR-CAD Server accesses to the implicitly linked parameter value which is constraining the right part of the guide curve (length = 110mm on Fig. 7). Thus, users can change this parameter value and deform the Rear-view mirror shape from a 3D interaction.

I used 4 parts of the mirror for the deformation task: LeftBottomCorner, RightBottomCorner, Bottom and RightSide (Fig. 9). In Scroll condition, shape evolution was consistent with user’s hand motion in RightSide and LeftBottomCorner: right hand motion led to shape deformation towards the right for both parts. On the contrary, it was inconsistent in RightBottomCorner and Bottom: right hand motion led to shape deformation towards the left for the RightBottomCorner and towards the bottom for the Bottom.

Method
The experiment had a [2 x 2 x 4] within-subject design with the three following factors:

- TECHNIQUE, with two levels: ShapeGuide and Scroll.
- FEEDBACK, with two levels: NoForce for which the magnetic force feedback is not available, and Force for which the magnetic force feedback is available.
- PART, with four levels: the 4 deformable parts of the CAD object.

The techniques used in each TECHNIQUE×FEEDBACK condition can be described as follow:

- Scroll, NoForce: the CAD part is modified with a horizontal scroll of users’ hand.
- Scroll, Force: in addition to Scroll, the magnetic force feedback adds some attractive points distributed on the horizontal axis.
- ShapeGuide, NoForce: the CAD part is modified in the direction of users’ gesture according to ShapeGuide algorithm.
- ShapeGuide, Force: in addition to ShapeGuide, the magnetic force feedback attracts the users’ hand to the closest shape proposed by the ShapeGuide algorithm.
TECHNIQUE and FEEDBACK are the two main factors, and trials are grouped by TECHNIQUE×FEEDBACK. The order of TECHNIQUE×FEEDBACK was counterbalanced across participants using a balanced Latin Square; the order of PART is counterbalanced for each TECHNIQUE×FEEDBACK.

Interaction device: ScaleOne Haptic device
The Scale-One is a redundant 10 dof haptic device from Haption composed of a Virtuose6D coupled onto a 4 dof carrier (Fig. 8, left). This device allows a participant to move anywhere in the CAVE system while grabbing virtual entity with the handle of the Virtuose providing collocated visuo-haptic interaction capability.

Participants
16 participants, aged between 20 and 63 (11 men and 5 women), were recruited.

Task
I asked participants to perform a deformation task of the Rear-view mirror CAD model. Fig. 9 shows the example of user interaction during the experiment. A virtual representation of a Virtuose handle is displayed on the virtual environment (Fig. 8, right). This virtual handle is co-localized with an actual handle of Scale-One in CAVE system, moving consistently according to the participant’s real hand motion. This virtual handle is used as an interaction pointer allowing the users to interact with the Rear-view mirror. The deformation scenario is composed of the following steps:

- **Selection** of a part: participants can select the part by pressing a button on the handle.
- **Modification**: after selection of a part, participants can switch between possible shapes by their hand motion. Once they reach the desired 3D shape, they can validate the deformation by pressing the same button once again.

For each trial, participants had to deform one PART of the Rear-view mirror from an initial shape to a targeted shape, i.e. from an initial parameter value to a targeted parameter value. Only this part of Rear-view mirror was modifiable at each trial, colored with Orange (Fig. 10). The targeted shape was displayed with a transparent yellow color (Fig. 10). If participants failed to deform the shape with the correct targeted parameter value, they had to select the part and attempt to deform the shape again. Once participants achieved the task, the next targeted shape appears.

Data Collection

I extracted four different measures from logged data at each trial: the Task Completion Time, the Wrong Direction Start rate, the number of Overshoots and the number of Errors.

- **Task Completion Time (TCT):** the TCT measured the total duration of the modification step during the deformation task.

- **Wrong Direction Starts (WDS):** I considered that the participants started their motion in the wrong direction if they started by deforming the part in the opposite direction to the targeted parameter/shape.

- **Overshoots:** an overshoot was counted when the participants reached the targeted parameter/shape, but continued their gesture further away to a higher or smaller parameter value. Several overshoots can be accumulated during one attempt.

- **Errors:** the number of Errors was computed from the number of wrong parameter/shape selections in a trial.

Finally, the questionnaire assessed the participant preferences. It was designed based of the NASA Task Load Index (TLX) [13]. I customized this by including one extra factor: Consistency (i.e. Did you find the interaction technique consistent with the shape deformation?). Consequently, the factors of the questionnaire were Mental Demand, Physical Demand, Difficulty, Frustration Experienced, Consistency and Performance Level. Participants had to grade each factor using a 5-point Likert scales.

### 2.6. Main results

**TCT:** ShapeGuide was significantly faster than Scroll (Fig. 11, TCT). There were no significant differences in FEEDBACK condition, and no significant interaction effect between TECHNOQUExFEEDBACKxPART.

**WDS:** ShapeGuide led to significantly less WDS than Scroll (Fig. 11, WDS).

**Overshoots:** ShapeGuide led to significantly more Overshoots than Scroll (Fig. 11, OVER1). However, force feedback significantly reduced the number of Overshoots in comparison to NoForce (Fig. 11, OVER2).

**Errors:** I did not observe any significant differences.

**Questionnaires:** Fig.12 illustrates the results of the subjective questionnaire. ShapeGuide was perceived less mentally demanding, less frustrating, less difficult to use and more consistent than Scroll. In general, ShapeGuide was also preferred by the participants in comparison to Scroll.
2.7. Discussion

The results of the experiment provide evidence that ShapeGuide technique significantly increases user performance on parametric modification of CAD data in comparison to a one-dimensional scroll technique. More precisely, participants were able to achieve the deformation task 42% faster with ShapeGuide than with the Scroll technique, which supports H1.

This improvement can be explained by a better consistency between shape deformation and user hand motion with ShapeGuide. In particular, we observed that ShapeGuide reduced of 80% the chance that participants move their hands towards the wrong direction at the beginning of their gesture, in comparison to Scroll. The subjective questionnaire also confirmed that the participants perceived ShapeGuide as more consistent that the Scroll technique. For all these reasons, H2 is validated.

In the subjective questionnaire, most of the participants reported that they preferred ShapeGuide to the Scroll, which supports H3. In particular, they found ShapeGuide less mentally demanding, less frustrating and less difficult to use.

A magnetic force feedback was an effective solution to reduce the number of Overshoots and thus, improved the precision of both techniques. Participants achieved the deformation task with 27% less Overshoots with the force feedback condition than without, which supports H4.

3. Summary

In the past years, I firstly studied the drawback and limitation of cReaRV, a VR-CAD system allowing the CAD data modification in a virtual environment. Then, I designed a new system architecture of cReaRV to deal with a heterogeneous platform and to study for intuitive CAD-data.
modification in 3D space. With this new VR-CAD system, I proposed and investigated a new 3D interaction technique, ShapeGuide. ShapeGuide allows users to modify parameter values of a CAD object by directly pushing/pulling its surfaces in an immersive environment. I conducted a controlled experiment to compare the efficiency of ShapeGuide for parametric modification with a one-dimensional scroll technique, and also to investigate the added-value of force feedback. The results of our experiment demonstrated the following points:

- ShapeGuide is faster than the scroll technique for a CAD-data modification.
- Shape deformation is more consistent with the user hand motion when using ShapeGuide.
- Most participants preferred ShapeGuide than scroll technique.
- ShapeGuide induced a number of imprecise manipulation at specific part.
- Force feedback can enhance precision of 3D manipulation for a CAD-data modification.

**Perspective for future work**

Although ShapeGuide enhanced the user interaction for parametric modification in a virtual environment, a precision for selection of desired shape should be improved. I am exploring solutions to solve this problem. A work in progress aims to take into account the orientation of the user hand regarding a pseudo-normal vector at a closest point on the surface for selecting a modified shape, namely “5dof Distance Computation” (5DC). I worked for 5DC algorithm with an internship student from a mathematic field. During his internship period, we implemented this algorithm in VHServer with a visual feedback using HTC-VIVE. The effect of this algorithm for a selection task will be investigated with user-study.

The system of ShapeGuide can address heterogeneous VR platforms. In order to keep a precise 3D manipulation without force feedback devices, I will investigate the usability of pseudo-haptic [14] on ShapeGuide.

In parallel, I will also work for collaborative scenario to optimize the design process of CAD design. ShapeGuide technique enables users to interact with one parameter at a time, but it might be also extended to modification of multiple coupled or balanced parameters, between different platforms. I am currently implementing our VR-CAD system on Wall-sized display (WILDER). After this implementation, I will investigate a remote collaboration for CAD data modification between CAVE and WILDER.

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*Signature*

Thesis director: Patrick Bourdot

Date: June 6th Place: Orsay Signature:
REFERENCES


