TOUCH AND DESIGN

HW AND SW TECHNOLOGY AND COGNITIVE ERGONOMICS UPDATE

by
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Abstract
This document describes the state of the art in the three main research fields of the project: haptic technology, advanced shape modeling technology and cognitive ergonomics. The present document is the third version of the original document issue which includes an update of state of the art concerning haptic devices and exoskeleton.

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0. Index

1. Extended Summary

This report includes the state of the art in the three main research fields of the project: haptic technology, advanced shape modelling technology, and cognitive ergonomics. The aim of the report is updating the state of the art in the three fields of interest, taking into account the objectives of the project. The report content will be used by the T’nD partners in order to build a common background on the different disciplines, and also as basis for the project developments.

The section on haptics aims at providing objective quantification of performances of current haptic technology, in respect to the project objectives. T’nD system should replicate the environment and the tools the designers are used to use in their daily work. Therefore, T’nD haptic device should provide a tool the designers can interact with using full hands, or in alternative it should provide typical clay modelling tools. Technically, that implies that the T’nD haptic system is required to provide at least continuous contact, and it has to be an active haptic device providing whole arm range motion. The report includes an overview of current commercial haptic products and lab prototypes. It also includes future and emerging technologies in order to be updated and to monitor the progress and the technological evolution trends. A section reports on benchmarking results concerning current available technology, considering haptic performance indicators such as workspace, position resolution, stiffness, nominal forces, and tip inertia, and also some non-dimensional performance indicators. Finally, the section lists some critical issues of current technology, always considered in respect to T’nD objectives. On the basis of the state of the art, the final conclusion highlights that an extended version of FCS HapticMaster is the most appropriate hardware solution for the project. The FCS HapticMaster can be used as basic platform, equipped with a strong and stiff 6-DOF device carrying simulated clay modelling tool with two handles.

The section on shape modelling aims at providing a survey of modelling techniques, and verifies current developments in commercial and academic systems, in order to identify the more suitable development context for T’nD. From the point of view of shape modelling, the project aims at defining a technique for shape generation and modification allowing a fine control of aesthetic properties of shapes. The technique should support the integration to the T’nD haptic system, and on the other side should interface to standard CAD data models. The report includes an overview of approaches for shape modelling techniques, ranging from purely geometrical representation up to physics-based approaches. Some recent techniques for shape generation/modification are particularly interesting for T’nD project: voxel modelling and “swept volumes” techniques. The section also includes some references to commercial products that use methods for shape generation, as said, sweep or voxel-based, highlighting the current problems they present in smooth shape generation. Besides, the report mentions as issues of possible interest recently developed physics-based methods that represent any object as a dynamic system subjected to internal interactions depending on materials, and external forces/stresses. On the basis of the state of the art analysis, the final conclusion highlights that the emerging technologies that the project will further investigate and develop include sweep-based and voxel-based techniques. The major open issue concerns the definition of an appropriate theory allowing discrete schemes to support fine quality shape generation.

The section on cognitive ergonomics provides and overview of recent findings in the field, considering the project objectives. From the user interface point of view, the aim of the T’nD project is providing a user-oriented system that is both useful and usable by designers. In this context, the analysis addresses issues related to design activity, gesture in design activities and treatment of haptic information. In particular, the report includes a description of the content of a survey on perception provided by haptic systems, mainly reporting those issues that are more related to T’nD objectives, such as manual exploration, haptic space perception, haptic memory, and others. For what concerns cognitive treatment of gestures in design activities particular attention is given to motor programs that consists of muscular activation instructions, always to be parameterized according to local and momentary information, coming from the various senses, particularly touch and kinesthesia, participating in the execution of the motion, under the supervision of sight. Of particular interest is “oriented morphokinesis” that refers to motions with a determined shape, such as the motions of a dancer or of a draftsman. The report highlights how the control of the shape and size of the motion during the performance are necessarily under some degree of cognitive control. Therefore, the notion of knowledge management can help in building a model of the activity. In the case of T’nD, the knowledge base could be thought of motor programs for morphokinesis, learned through the training and professional practice of the performer. On the basis of the state of the art analysis, the final conclusion points put the necessity to extend usual ergonomics criteria and principles with new aspects that will be developed analyzing T’nD designers’ cognitive processes. The new principles will then be adapted to the specifications of T’nD haptic and shape modelling systems.

The last section reviews some ongoing activities aiming at integrating haptic systems with modelling environments, with particular reference to shape generation. None of the ongoing works found in literature addresses and provides solutions for shape modeling and modification issues as required in the T’nD project.

2. Haptic technology update

2.1. Introduction

Haptic (or force feedback) devices are gradually penetrating commercial market segments. The past five or ten years have seen a considerable increase in the number of commercially available haptic products. This report serves to clarify the pros and cons of these products in the context of the Touch and Design project, by an objective quantification of the performance of haptic products.

Haptic devices can be ordered in many ways. One taxonomy (Thomson, expanded here) classifies devices as follows :

- joysticks (and other steering devices like wheels, pedals)
- medical devices (simulating specific medical tools, usually laparoscopic)
- rehabilitation devices
- finger-based or whole arm devices
    - exoskeletons
    - end effector devices
    - wire devices
- active surface displays (actively shaped membranes, pin cushions, etc.)

Other important dichotomies used for classifying haptic technology are the following:

- impedance versus admittance controlled
- parallel versus serial mechanisms
- continuous contact versus "encountered" devices
- active versus passive (Magneto-Rheological or hybrid) devices
- haptic versus tactile displays

In the context of Touch and Design, we will limit ourselves to *continuous contact*, *active haptic devices* with a *whole arm range of motion*. Tactile information (producing tactile feedback on an operators' skin) may be added at a later stage.

This report sets out to parameterize the haptic performance of these devices by objective performance indicators, which are obtained from available product specifications. The devices are compared according to the following specifications:

- workspace
- position resolution
- tip inertia and friction
- stiffness
- nominal and maximum force

Three additional, non-dimensional performance indicators are derived and used :

- position ratio (or relative positioning resolution)
- force ratio (or relative force sensitivity)
- inertial ratio (or dynamic range)

These performance parameters are set into the perspective of the historical and future development of the field, and in particular in the perspective of the Touch and Design project needs.

2.2. Commercial products

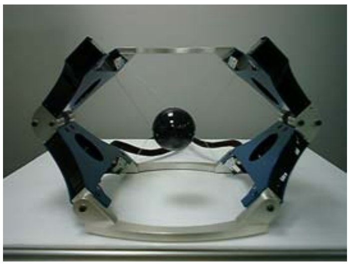
This section gives an alphabetical overview by manufacturer, of commercial haptic devices currently available. All commercial devices available are point-based devices, except for the Immersion Cyberglove.

Laparoscopic trainers and force feedback joysticks have been excluded from this survey because they have no bearing on the T’nD project.

Cyverse - www.cyverse.co.jp

Spidar G - 6-DOF ball on cables

workspace [liters]	8	liters
price 6-DOF	24,500.-	€



FCS Control Systems - www.fcs-robotics.com

HapticMASTER

workspace	66	liters
pos. resolution		0,004 mm
stiffness	50	N/mm
max. force	250	N
nom. force	100	N
tip inertia	2	kg
price	42.500,00	€

Force Dimension - www.forcedimension.com

Omega

workspace	0.7	liters	
pos. resolution		0.02	mm
stiffness	*	N/mm	
max. force	15	N	
nom. force	15	N	
tip inertia	0.15	kg	
price	*	€	

Delta

workspace [liters]	3.4	liters	
pos. resolution		0.1	mm
stiffness	*	N/mm	
max. force	25	N	
nom. force	25	N	
tip inertia	*	kg	
price	*	€	
price 6-DOF	*	€	

Haption Virtuose - www.haption.com

Virtuose 3D

Virtuose 6D10-20

No specs available

Virtuose 6D35-45

workspace	90	liters
pos. resolution	0.2	mm
stiffness	4	N/mm
max. force	35	N
nom. force	10	N
tip inertia	*	kg
price	*	€
price 6-DOF	*	€

Virtuose 6D40-40

workspace [liters]	64	liters
pos. resolution	0.2	mm
stiffness	4	N/mm
max. force	40	N
nom. force	20	N
tip inertia	*	kg
price	*	€
price 6-DOF	*	€

Immersion - www.immersion.com

Cyberforce

workspace	45	liters
pos. resolution	0.06	mm
stiffness	*	N/mm
max. force	8.8	N
nom. force	6.6	N
tip inertia	*	kg
price	*	€
price 6-DOF	*	€

Cybergrasp

force reflecting glove

MPB Technologies - http://www.mpb-technologies.ca

Freedom 6S

workspace	12	liters
pos. resolution	0.02	mm
stiffness	*	N/mm
max. force	2.5	N
nom. force	0.6	N
tip inertia	0.25	kg
price	*	€
price 6-DOF	*	€

Sarcos - www.sarcos.com

Sarcos Dextrous Arm - master slave system

no specs available

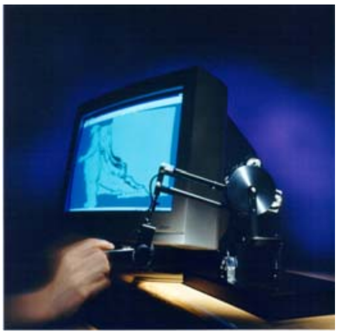
Sensable - www.sensable.com

Phantom Omni / Desktop

workspace	3	liters
pos. resolution	0.02	mm
stiffness	3.2	N/mm
max. force	6.4	N
nom. force	1.7	N
tip inertia	0.08	kg
price	~ 12,000.-	€

Phantom Premium 1.0

workspace	6	liters
pos. resolution	0.03	mm
stiffness	3.5	N/mm
max. force	8.5	N
nom. force	1.4	N
tip inertia	0.08	kg
price	21,000.-	€



Phantom Premium 1.5

workspace	20	liters
pos. resolution	0.03	mm
stiffness	3.5	N/mm
max. force	8.5	N
nom. force	1.4	N
tip inertia	0.08	kg
price	27,500.-	€
price 6-DOF	55,000.-	€

Phantom Premium 3.0

workspace	200	liters
pos. resolution	0.02	mm
stiffness	1.0	N/mm
max. force	20	N
nom. force	3	N
tip inertia	0.15	kg
price	61,000.-	€

2.3. Lab prototypes

There are numerous lab prototypes of haptic devices. The impression is that every development starts from scratch, and it depends on the ingenuity of the maker whether it is successful. None of these devices have gone into production, with the exception of one, the McGill devices, which is marketed by MPB Technologies, as listed in the previous section.

The devices fall into two broad classes:

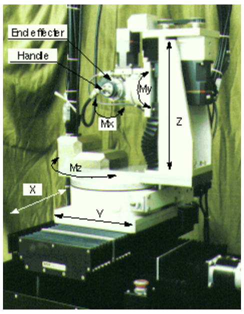
- small and light proof of concept devices
- extremely large exoskeleton devices

This section lists a number of the more interesting devices alphabetically.

Web addresses are given where possible to allow interested readers to access the data available.

AIST (Japan) 6 DOF force feedback input device

http://staff.aist.go.jp/yamashita-juli/projects/ForceFeedbackDevice.html



Carnegie Mellon University USA MagLev

Magnetic levitation device.

http://www-2.cs.cmu.edu/afs/cs/project/msl/www/haptic/haptic_device.html
http://www-2.cs.cmu.edu/afs/cs.cmu.edu/project/msl/www/virtual/virtual_desc.html

CEA LIST (France)

CEA-LIST has recently developed a new six degrees of freedom haptic device for desktop applications emphasizing quick and precise manipulation. The device relies on a light parallel architecture connecting the base of the robot to the mobile platform manipulated by the user. It is dimensioned and optimized to fit design requirements associated with CAD or virtual sculpting.

The research group has also developed a new wearable haptic device allowing fine manipulation with thumb and index fingers.

http://www-list.cea.fr/gb/index_gb.htm

FIBO (Thailand) 6 DOF haptic device

http://fibo.kmutt.ac.th/project/eng/current_research/haptic_interface.htm

Georgia Institute of Technology (Georgia Tech) Passive and active haptic devices

http://imdl.me.gatech.edu/haptics/index_main.html

Hanyang University Korea 6 DOF haptic interface & gripper

http://robotics.hanyang.ac.kr/research.html

Iwata Lab - VR Lab, University of Tsukuba - Haptic Master

http://intron.kz.tsukuba.ac.jp/vrlab_web/hapticmaster/hapticmaster_e.html
Inventor of the name "haptic master".

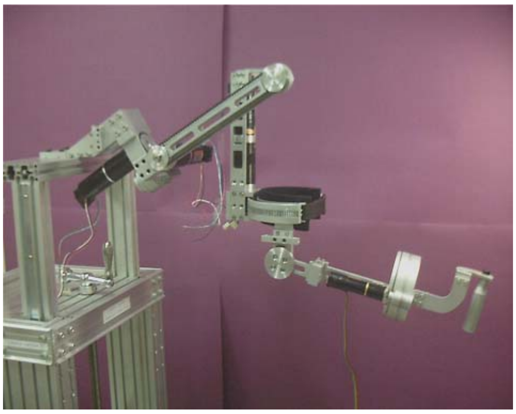
Johns Hopkins University Haptic scissors

Haptic display for teaching.

http://www.haptics.me.jhu.edu/research/#tools

Korea University KU-AM3 5 DOF haptic device

http://mecol.korea.ac.kr/eng_main.htm



McGill University (Canada) Freedom 7

http://www.cim.mcgill.ca/~haptic/pub/VH-ET-AL-ISER-98.pdf
Pantograph.
http://www.cim.mcgill.ca/

MIT Touchlab - grippers/graspers,

http://touchlab.mit.edu/index.html

Northwestern University 4 DOF haptic interface

http://lims.mech.northwestern.edu/projects/index.htm
6 DOF haptic interface

PERCRO Italy 6 DOF haptic interface

PERCRO lab has recently presented the L-EXOX (Light Exoskeleton). It is an exoskeleton based haptic interface for the human arm. The L-Exos has been designed as a wearable haptic interface, capable of providing a controllable force at the center of user's right-hand palm, oriented along any direction of the space. It is a 5 DOF robotic device with a serial kinematics, isomorphic to the human arm. It is suitable for applications where both motion tracking and force feedback are required, such as human interaction with virtual environments or teleoperation/telemanipulation tasks.

PERCRO lab has also developed an active haptic thimble that is a portable device that can be fixed on the user's finger and is endowed with an actuation system that controls the motion of a platform, to bring it in contact with the fingerpad with different orientations and at different fingerpad locations. In this way, the device should provide a sufficient feeling of the curvature of the objects.

http://percro.sssup.it/~antony/research/desktop/6_dof.htm

SML Japan **6 DOF haptic interface**

http://www.space.mech.tohoku.ac.jp/research/haptic/haptic-e.html

Tokyo University Japan **PWDM**

http://www.mech.titech.ac.jp/~msd/takeda/WireHaptic(1998).htm

University of Berlin **ViSHaRD6**

http://rs.tu-berlin.de/wwwrt/publ/docs/640.pdf

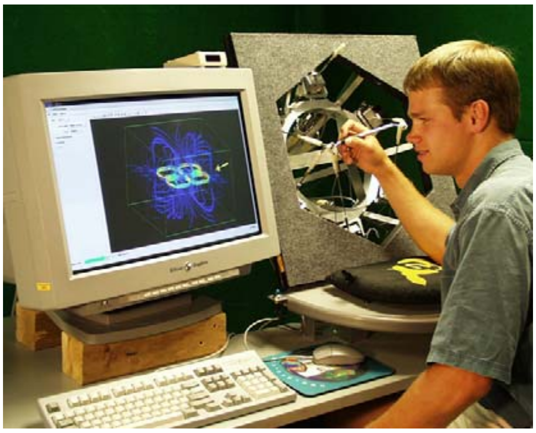
University of Bologna **WireMan**

http://www-lar.deis.unibo.it/activities/videt/mechanics.html

University of Colorado **5-6 DOF haptic interface**

Pen based 5-DOF interface on sticks between rollers.

http://osl-www.colorado.edu/Research/haptic/hapticInterface.shtml

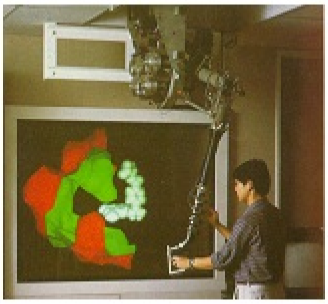


Université Laval (Canada) **SHaDe**

http://wwwrobot.gmc.ulaval.ca/recherche/theme03_a.html

University of North Carolina at Chapel Hill **UNC-CH**

Strong in haptics, the system use old Argonne arms and Phantoms as tools.



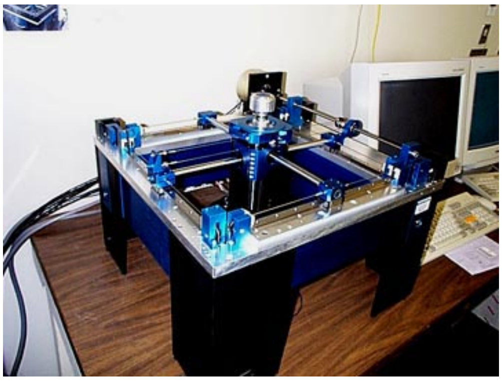
University of Padova **2 & 3 dof haptic devices**

http://www.dei.unipd.it/~oboe/haptic.html

University of Washington **Linear Haptic Display - Excalibur**

One of the very few stiff admittance controlled devices. Did not reach production.

http://brl.ee.washington.edu/Research_Active/Haptics/Device_04_LHD/LHD.html



University of Wisconsin **Haptic Gripper**
http://mechatron.me.wisc.edu/papers/imece99b.pdf

2.4. Future and emerging devices

The previous sections have shown the state of the art in point based haptic interfaces.

Mechanically these can be divided into serial robots, parallel robots, and wire "spiders". From a control point of view, they are divided into "admittance controlled" devices driven by a force sensor, as typified the FCS HapticMaster, and lightly built impedance controlled devices, by far the majority of the devices available.

Admittance controlled devices such as the FCS HapticMaster are the most recently emerging ones. The addition of the force sensor allows devices with much larger workspace and at the same time, larger forces and stiffnesses.

Future devices may use an entirely different paradigm as yet unknown. The taxonomy in the introduction mentioned a number of alternative options such as "encountered" membrane devices, but it is not foreseen that these will affect the field of haptics, as much as the field of tactile displays.

2.5. Benchmarking of current technology suitable for T’nD

Haptics is an emerging field, and there are as yet no hard and fast rules on what constitutes an optimal haptic interface. A number of tentative metrics have been proposed in literature, such as the Z-width (the dynamic range of achievable impedances). The bottom line is that an ideal haptic interface should be able to render every feeling, ranging from "free air", i.e. no inertia and no friction, to "infinitely stiff walls" or "heavy objects", i.e. high force and stiffness.

Product specifications used below to approximate these requirements include:
- workspace
- position accuracy
- stiffness
- nominal and maximum force
- tip apparent inertia and friction

These performance indicators can in many cases be obtained from available product information. The tables on the next pages report performance indicators for a number of commercially available haptic devices (listed in section 2.2). Performance indicators of the FCS HapticMaster which will be used in the project are highlighted by shading. Only the parameters for the translational degrees of freedom are considered in order to allow comparison of as many different devices as possible.

The table below gives some analogies between performance indicators of visual devices, and possible performance indicators of haptic devices.

visual performance indicators		**haptic performance indicators**	
screen size	[inches]	workspace	[liters]
resolution	[pixels]	haptic resolution	[voxels]
color depth	[bits]	force depth	[increments]
contrast		stiffness	

Workspace

The workspace of the commercially available haptic devices varies significantly. Based on the kinematics of the device, the workspace volume in liters is estimated. The table below orders the devices by workspace volume.

	Workspace [liters]
Phantom Prem. 3.0	203
Virtuose 3D	189
CyberForce	102
HapticMaster	80
Phantom Prem. 1.5	21
Delta HD	20
Freedom 6S	11
Phantom Prem. 1.0	6
Phantom Desktop	3

Position resolution

Position resolution is a key parameter for a haptic device. It largely determines the smoothness of virtual objects, especially for stiff objects. For impedance controlled haptic devices (most commercially available haptic devices) the position resolution at the end effector is also related to the maximum stiffness that can be rendered, because a displacement must be measured before force can be generated. For admittance controlled haptic devices (like the HapticMaster) this is not the case. In the table below the devices are ordered by absolute end effector position resolution.

	Pos. res. [mm]
HapticMaster	0.004
Phantom Prem. 3.0	0.02
Freedom 6S	0.02
Phantom Desktop	0.02
Phantom Prem. 1.5	0.03
Phantom Prem. 1.0	0.03
CyberForce	0.073
Virtuose 3D	0.1
Delta HD	0.1

Stiffness

Stiffness is a key haptic parameter, because it determines the ‘crispiness’ of the device. It is difficult to achieve both mechanically and control wise, especially in impedance controlled devices. However, a high haptic stiffness is the only way to reflect a virtual world with rigid objects accurately. The table below orders the devices by maximum stiffness.

	max. stiffness [N/mm]
HapticMaster	50.0
Delta HD	12.5
Phantom Prem. 1.5	3.5
Phantom Prem. 1.0	3.5
Phantom Desktop	3.2
Freedom 6S	2.5
Virtuose 3D	2.3
CyberForce	(2)
Phantom Prem. 3.0	1

Nominal force

The nominal force that a haptic display can render depends on the strength of the mechanics and the motors. The maximum forces are typically a factor of 2.5 higher than the nominal forces.

	continous force [N]
HapticMaster	100
Delta HD	20
Virtuose 3D	11
CyberForce	6.6
Phantom Prem. 3.0	3
Phantom Desktop	1.7
Phantom Prem. 1.5	1.4
Phantom Prem. 1.0	1.4
Freedom 6S	0.6

Tip inertia

Minimal equivalent inertia at the tip of the end effector, or simply the tip inertia, is an important performance indicator. It determines the lightest object or feels that can be rendered.

For impedance controlled haptic devices the minimal end effector inertia equals the physical end effector inertia of the mechanical device. For admittance controlled devices the physical inertia can be partly eliminated by the control loop.

	tip inertia [kg]
Phantom Desktop	0.08
Phantom Prem. 1.5	0.08
Phantom 6 DOF	0.09
Delta HD	(0.1)
Phantom Prem. 3.0	0.15
Phantom Prem. 1.0	0.15
Freedom 6S	0.25
CyberForce	(0.25)
Virtuose 3D	(0.4)
HapticMaster	2

(..) = estimated value

Non-dimensional performance indicators

The product specifications discussed above reflect an important part of the haptic performance. However, additional performance indicators are required to complete the definition of haptic performance. We will define the following non-dimensional parameters:

- position ratio.
- force ratio.
- inertial ratio.

Position ratio

Except for the FCS HapticMaster, most large-workspace haptic devices have less position accuracy at the end effector than small-workspace devices. This is to be expected, since for articulated devices rotational measurements of the joints must be increasingly accurate with size to obtain the same positional accuracy at the tip.

To correct for size influence, the one-third power of the workspace is divided by the linear position resolution. We call this quantity the position ratio. It gives an approximation of the number of haptic voxels that the device can render in a linear direction. So it is a measure for the haptic resolution. The table shows that haptic devices have a much higher spatial resolution than visual displays. The human hand is much more sensitive to very high spatial and temporal frequencies than the human eye.

	linear number of voxels
HapticMaster	110 000
Phantom Prem. 3.0	29 400
Freedom 6S	11 000
Phantom Prem. 1.5	9 000
Phantom Desktop	7 000
CyberForce	6 400
Phantom Prem. 1.0	6 000
Virtuose 3D	5 800
Delta HD	2 700

Force ratio

In impedance controlled devices more power implies more mass and more friction. Impedance controlled devices are unable to render forces below the back drive friction, so this is the smallest increment for force rendering. In admittance controlled devices, the resolution of the force sensor is the limiting factor. Dividing the nominal force by the back drive friction yields the number of force increments over the workspace. We will call this quantity the force ratio or relative resolution.

	Friction [N]	**relative force resolution**
HapticMaster	0.01	10 000
Phantom Prem. 1.5	0.04	35
Phantom 6DOF	0.04	35
Phantom Prem. 1.0	0.04	35
CyberForce	0.2	33
Phantom Desktop	0.06	28
Virtuose 3D	0.4	28
Delta HD	1.3	15
Phantom Prem. 3.0	0.2	15
Freedom 6S	0.06	10

Inertial ratio

It is not significant to compare the tip inertia of a big and strong device with the tip inertia of a smaller device. To correct for this, the tip inertia is divided by the maximum stiffness of a haptic device. We define this ratio to be the inertial ratio. It can be tentatively converted into a mechanical bandwidth, since the square root of stiffness divided by the mass represents a frequency. The conversion is seen to hold for the FCS HapticMaster at least.

	inertial ratio 10^{-3} **[s^{-2}]**	**mechanical bandwidth [Hz]**
Delta HD	(0.008)	(55)
Phantom Desktop	0.024	32
Phantom 6DOF	0.026	31
HapticMaster	0.04	25
Phantom Prem. 1.0	0.043	24
Phantom Prem. 3.0	0.05	22
Freedom 6S	0.1	16
CyberForce	(0.13)	14
Virtuose 3D	(0.17)	12
Phantom Prem. 1.5	0.21	11

2.6. Critical issues related to T'nD technology

The Touch and Design project has the objective to create an interface that will allow designers to interact haptically and graphically with virtual models of products including a true size car body. Purely point based haptic interaction will not suffice to appreciate and modify the surfaces in an intuitive way. Designers will wish to interact either with the full hand, or with a virtual version of typical clay modeling tools.

Satisfactory full hand interfaces (haptic gloves) have not been built so far, despite a number of attempts and one commercial product (the Immersion Cyberglove). This is probably a bridge too far at the current state of the art.

A more feasible option is to allow two-hand interaction with a typical clay modeling tool. This can be done by displaying all forces and torques on a physical realization of the tool, or at least on the two handles of the tool. This will require a 6-DOF haptic device with the suitable workspace and force rendering capabilities.

A number of 6-DOF devices have been built, but since they were all of the impedance controlled variety, they are lacking in overall, and especially rotational, strength and stiffness. The FCS HapticMaster on the other hand is the only device which has the strength in an acceptable price bracket, but it is currently a 3-DOF to 4-DOF device.

Attempts have been made to use two point based interfaces (two Phantoms) to drive a 5-DOF or 6-DOF end effector together, or to give a 5-DOF effect by using a separate device for the thumb and one for the index finger. One possible option would be to take two devices of suitable strength and stiffness, e.g. two FCS HapticMasters, and use these in this way. However, the solution is a cumbersome one.

The most attractive option is to add the rotational degrees of freedom to a FCS HapticMaster.

2.7. Conclusions

This chapter gave a full overview of the haptics arena at the current time. The table below summarizes the benchmark results from earlier sections. The performance indicators are classified as follows: ++ for 1st place, + for 2nd place, o for 3rd and 4th place, - for 5th to 8th place, and - - when lower.

Some haptic devices have an optional end effector with a gimbal that offers 3 extra passive or active degrees of freedom. The devices are listed by these functional groups, viz.: 3 DOF active, 3 DOF active & 3 DOF passive, 6 DOF active, and others.

From the discussion of critical technology given in the previous section, we conclude that the most attractive option is to develop strong *and stiff 6-DOF device carrying simulated clay modeling tool with two handles, and using the FCS HapticMaster as a platform.*

	workspace	position resolution	stiffness	nominal force	tip inertia	haptic resolution	force depth	inertial ratio
3 DOF ACTIVE								
Delta HD	-	-	+	+	(o)	- -	-	(++)
Phantom Prem. 1.0	- -	o	o	-	-	-	o	-
Phantom Prem. 1.5	-	o	o	-	++	-	o	- -
HapticMaster	o	++	++	++	- -	++	++	o
Phantom Prem. 3.0	++	o	-	-	-	+	-	-
3 DOF ACTIVE & 3 DOF PASSIVE								
Phantom Desktop	- -	o	o	-	++	-	-	+
CyberForce	o	-	-	-	(-)	-	o	(-)
Phantom Prem. 1.0	- -	o	o	-	o	-	o	-
Phantom Prem. 1.5	-	o	o	-	++	o	o	- -
Virtuose 3D	+	-	-	o	(-)	- -	-	(- -)
HapticMaster	o	++	++	++	- -	++	++	o
Phantom Prem. 3.0	++	o	-	-	(-)	+	-	-
6 DOF ACTIVE								
Delta HD	-	-	+	+	(o)	- -	-	(++)
Freedom 6S	-	o	-	- -	-	o	-	-
Phantom 6DOF	-	o	o	-	+	-	o	o
FORCE FEEDBACK GLOVE								
CyberForce + Grasp	o	-	-	-	(-)	-	o	(-)

2.8. References

The sections above give web addresses for most of the devices mentioned. The following web contains an overview of all kinds of haptic devices, including tactile and encountered devices:

http://www.cs.utah.edu/~tthompso/haptics.html
http://haptic.mech.northwestern.edu
http://www.roblesdelatorre.com/gabriel/hapticsl

A number of books and articles give recent overviews of the haptics field and of possible performance criteria:

Burdea GC, '*Virtual reality technology*',
2003 John Wiley, ISBN: 0-471-36089-9.

Hayward V et al., *'Performance measures for haptic interfaces',*
in : Robotic Research: the 7th Int. Symp. G.G. Hirzinger (eds.),
1996 Springer Verlag, pp. 1995-207.

Hayward V et al., *'Haptic Interfaces and Devices'*,
in : Sensor Review, Vol.24, number 1 (2004), pp.16-29.

Laycock, SD et al., *'Recent Developments and Applications of Haptic Devices*,
in : Computer Graphics forum, Vol. 22 (2003), number 2, pp.117-132.

3. Shape modeling technology update

3.1. Introduction

3.1.1. The pioneers

De Casteljau, Coons, Bezier, Fergusson, Melhum, Sabin became preoccupied with the representation of complex industrial surfaces very early on, first in a confidential manner towards the end of the 50's then by publications towards the middle 60's, so well before the solid modelers[1]. The applications were essentially situated in the aeronautical, automobile and naval construction fields.

Bezier's work on the representation of explicit polynomial parametric curves and surfaces in the Bernstein base (Forrest, 1972) has allowed a real control of complex shapes. It has been demonstrated (P-J Laurent) that this base is the best one possible in terms of "similarity to the final shape".

This technique was then taken up again for representations by continuous C^k pieces[2] i.e. first the *B-splines* (about the mid-70's) (Gordon and Riesenfeld, 1974) then the *NURBS*[3] (towards the end of the 70's - beginning of the 80's) (Piegl and Tiller, 1995). Representation by pieces allowed greater flexibility for local definitions and deformations, but we will see further on that it is not without drawbacks.

More so than the representation in the Bernstein base it is the unified model approach that enabled rapid progress. There was one single type of representation with an approximation of everything that could not be expressed directly in this base. This reduced notably the combinatory explosion in the number of algorithms to be developed. Unfortunately, since the polynomials did not allow the representation of all the conic sections, a large proportion of the mechanism surfaces were the subject of approximations.

3.1.2. Improvements

The arrival of NURBS made it possible to think that this limitation had been overcome[4]. But with a little hindsight, one can pose the question of the profitability of this representation especially insofar as a required developer high skill level is concerned.

Then, in the 90's, *object oriented* (OO) languages and programming gave developers the illusion of independence with regard to representation. The procedural definitions of surfaces came in to complement that of the NURBS. The combination of processes seemed much less heavy to bear … but they entailed another sort of dependence (data processing) - more pernicious because more difficult to master for a "standard developer".

Around the same period *subdivision techniques* [http://graphics.cs.ucdavis.edu/CAGDNotes/] began to be known. They are mainly used for entertainment applications. They are based on a recursive refinement of an original polygonal or polyhedron, conveying a rough representation of the shape that leads to a final smooth one. These techniques allow creating a large spectrum of shapes but do not give the final right and tight control required in the industrial design market such as in car industry or home appliances.

Finally, starting in the 80's and accelerating in the middle of the 90's, due to the robotic industry and the NC machining requirements, shapes produced by the motion of solids (*swept volumes*)

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[1] The real beginnings of the Euclid solid modeler date from the mid 70's. It was based on a representation of shapes by facets.

[2] The first k derivatives (unless singularity) are equal on each side of the boundary between two pieces.

[3] **N**on **U**niform **R**ational **B**-**S**plines.

[4] Rational polynomial functions enable the representation of parts of conic sections.

have been studied [www.engineering.uiowa.edu/~amalek/sweep/sweeptV.htm]. The increase of the computer power helped a lot this evolution. This last method encompasses the one we want to use in our project; hence we focused mainly on it in the following state of the art.
After this very brief CAD complex surface history, let us see where we are today.

3.2. Shape modelling methods and techniques

A very important task in the design of complex-shaped products is shape modification applied to fit local/global aesthetic requirements and/or engineering constraints. The recent literature on shape modelling techniques shows a wide variety of approaches, ranging from purely *geometrical* representation/modification criteria, either by surface or volume modelling, up to *physics-based* 1D/2D/3D models, which incorporate constitutive material properties and physical laws describing the effects of an external environment on the shapes/materials. In the next Sections we mention some well-known geometrical and physical approaches for shape modification and deformation, focusing on more recent techniques with a more strict connection with our work.

3.2.1. Geometric modelling approaches

Shape modification techniques involve different geometric modelling aspects like: shape fairing, local correction, global deformation, shape optimisation, etc. Details on classical geometrical shape modelling techniques are well presented in Farin's overview (Farin, 2001).

The geometric models supported by most CAD/CAS systems are generally based on curves and surfaces represented by NURBS where the rational aspect is almost never used in the design step of stylistic shapes. The generation and manipulation of such shapes are obtained by acting on some low level parameters (control points and weights when rational is used) (Piegl and Tiller, 1995) (Farin, 1993). Although it is still extensively used, this technique is time consuming and neither sufficiently intuitive for the users nor definitively adapted for patchworks of trimmed entities[5].

Among classical methods for shape modification, *local* shape variations, as shown in the precursor work by Forsey et al. (Forsey and Bartels, 1988), are typically obtained from local refinement of free form shapes by means of hierarchical B-splines or NURBS functions. As concerns *global* deformation, as shown in the pioneer work by Barr (Barr, 1984), continuous variation of curves and surfaces is obtained by means of operators for scaling, rotating, tapering, twisting, and bending. The idea of deformation as a mapping from/onto 3D space is formalized in the so-called *free form deformation* (FFD) approach, in which free form shapes are embedded in 3D lattices defined by control vertices, then deformed by displacement of lattices' control vertices, as shown in the precursor works of Sederberg et al. (Sederberg and Parry, 1986), Coquillart (Coquillart, 1990) and successive generalizations. Shape smoothing and optimisation is typically carried out by minimization of functionals describing curvature variation (Farin and Sapidis, 1989) (Welch and Witkin, 1992).

The main drawback of the above techniques is that they require non-intuitive manipulation of low-level parameters of B-splines or NURBS representing shapes, together with a large number of inputs from the users. Subdivision techniques are also particularly used nowadays (and even for physical approaches to support particle-based models, as shown in the next Section), even though with them it is difficult to reach the quality level required in some high-end aesthetic domains. The final shape is not completely and directly "user-predictable" and, considering the level of modification details that some stylists require for reaching the final shape, we doubt that they can be used to generate stylistic object conveying specific characters such as car bodies, for instance. *Up to some extents the NURBS generation can be considered as a subset of subdivision techniques thus suffering the same drawbacks*.

The two sets of pictures below extracted from http://graphics.cs.ucdavis.edu/CAGDNotes/ illustrate how difficult it is to predict the final shape. Each column represents a family of shapes due

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[5] The so-called **B***oundary* **rep***resentation* (Brep)

to two different subdivision methods. On the left column it is the Doo-Sabin's method and on the right column Catmull-Clark's one. It is clear that we are far from an adequate tool to refine the quality of some aesthetic properties such as reflection lines (see below in § *Sweep-based*).

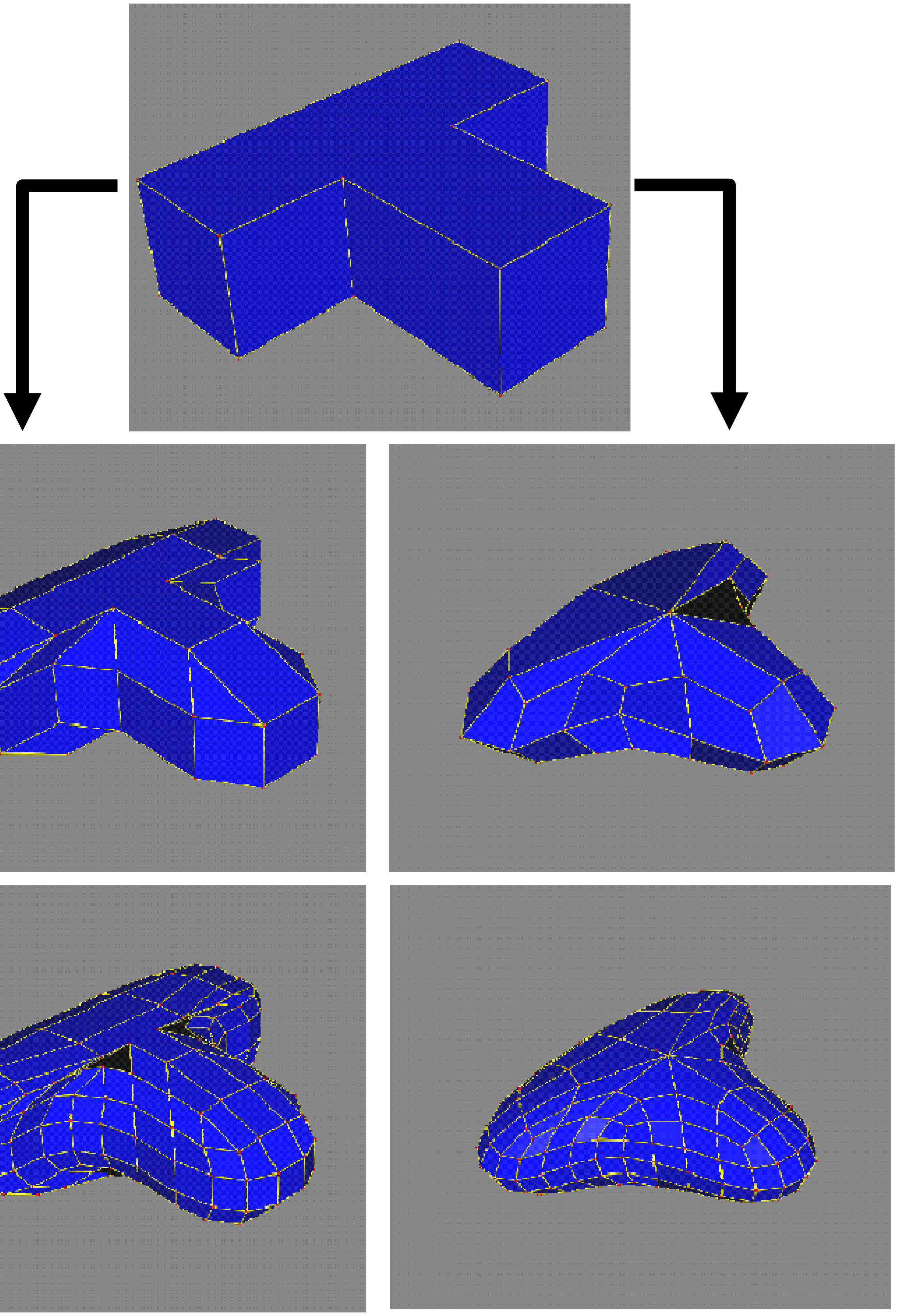

Fig. 1 - Doo-Sabin's VS Catmull-Clark's methods

Alternative deformation techniques have thus been recently developed, based on the extension of the well-known *feature* concept from solid modelling to free form modelling, to provide users with an easier and more intuitive control of the surface shape: Cavendish (Cavendish and Marin, 1992); Wyvfill et al. (Wyvill, Mc Robie et al.); Krause et al. (Krause, Stiel et al., 1998), Fontana et al. (Fontana, Giannini et al., 2000), and several other works. Interesting results have been achieved by the CEC project FIORES (http://www.fiores.com), providing a formalization of aesthetic properties of freeform shapes, and a set of tools for achieving and checking the quality of shapes in the process of engineering aesthetic shapes in reverse. This project succeeded in facilitating the modifications of shapes by defining/controlling the objectives (aesthetic properties) rather than the model itself. The CEC project FIORES-II aimed at proposing semantic-based operators to modifying shapes. These operators preserve/modify the shape aesthetic characters. Nevertheless none of the above attempts considers the first phase of the design, i.e. the first shape generation.

Some research studies have developed techniques for volume sculpting and morphing based on *voxel modelling,* i.e. discrete shape representation/manipulation by a grid of small elemental volumes*,* as shown in Galyean et al. (Galyean and Hughes, 1991); Lerios et al. (Lerios, Garfinkle, et al., 1995). Krause et al. (Krause, Stiel et al., 1998). Voxel modelling seems to be an interesting and effective approach to pursue for deformation modelling. Although good shape quality has been obtained by voxel models, further research work has to be done to provide user-friendly and intuitive tools for free form shape modelling. Moreover the additional work to transfer the voxel model into standard CAD data is still a source of problems.

So far, we have mainly discussed recent techniques for modification/deformation of existing shapes. The voxel modelling approach constitutes an alternative to direct low-level parametric surface definition even for *shape generation*, when relevant, obtained as a modification of an initial block of material. Removal or addition of matter is performed by ways of form features or algorithmic voxel removal or addition. So far, the voxel removal or addition techniques are used for generating organic shapes but with the current paradigm they are not at all suitable for generating smooth large shapes. The main reason is that the tools to remove or add voxels have a too short-distance scope. Moreover when the shape corresponds to the “organic” criteria, the mandatory data translation into standard CAD data for the downstream treatments leads to a classical shape generation way with the well known difficulties of surface reconstruction. The easiness and flexibility provided by the voxel approach is lost by this translation step.

Shapes generated by the motion of solids have been recently deeply studied. This technique is also called “*swept volumes*”, as mentioned in §3.1.2. Among several publications one from K. Abdel-Malek, D. Blackmore and K. Joy (Abdel-Malek, Blackmore e al., 2002) is a rather exhaustive survey (a web page is accessible at Iowa University – www.vrac.iastate.edu). Swept Volumes are usually used for NC machining simulation, robotic and kinematics, assembly planning, space management and interference checks and ergonomics. But it seems from our state of the art analysis that almost no company but one[6] used this technique to generate high quality aesthetic shapes. In almost in-house-made or marketed CAD systems there are sweeping algorithms for generating surfaces but they are mainly based on curve motion and their target is almost for mechanical engineering applications. It must be noted that based on the computation of curve and/or surface envelops, sweeping allows large-distance influences. Provided that the motion is smooth enough, envelope has smooth parts and in general … singularities. If the motion is not too complex the final shape is rather predictable. The drawback is the mathematical complexity for determining the envelope solution with an explicit representation while eliminating when relevant[7] some of the singularities.

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[6] The authors of these lines worked on this technique during the period 1990 – 1994 as the provider of the CAS kernel for a large Japanese car manufacturer company but never published due to confidentiality constraints. The CAS system is currently re-written on a new kernel.

[7] It might happen that a singularity must stay in the model, for instance when a G1-discontinuous edge is required.

3.2.2. Physics-based modelling approaches

A parallel field of research concerns shape modelling by using physical laws. More accurate than geometrical approaches, *physics-based* techniques represent 1D/2D/3D objects as dynamic systems subjected to internal interactions depending on materials, and interacting with an external environment through external forces/stresses, possible collisions and constraints. Several physical contexts have been considered, e.g., discrete dynamics, structural mechanics, elasticity theories, fluid dynamics, etc. (Gibson and Mirtich, 1997) (Barr and Witkin, 1997).

Among physics-based techniques, c*ontinuous* models interpret shapes as continuous media, e.g. subjected to laws from structural mechanics, generally leading to PDE models and solved by *finite element methods* (FEM$^)$ (Spyrakos, 1996) or other space (or space-time) discretization techniques. One of the most typical continuous approaches, pioneered by Terzopoulos et al. in '87-‘88 (Terzopoulos and Fleisher, 1988), finds deformed shape configurations by computing displacement functions from original equilibrium positions considering Lagrange equations in continuous formulation, as well as stationary/time dependent elasticity/plasticity laws (James and Pai, 1999). Shapes can be smoothed and sculpted with *energy-based* deformable models, by minimization of energy functionals describing stretching/bending/shear terms, as shown in Celniker et al. (Celniker and Gossard, 1991), and in many successive works.

In *discrete* physical formulations, shapes are modelled as systems composed of a finite number of mechanical constitutive elements subjected to certain static/dynamic laws. *Dynamic free-form deformation* is the dynamic counterpart of free form deformation, in which control points of lattices are nodes of force networks whose displacement is guided by force inputs driving locally or globally the deformation, as shown in Guillet and Leon (Guillet and Leon, 1998) and successive works. Recently, this approach has been coupled with free form feature modelling for aesthetic design, within FIORES-II tasks (Pernot, Falcidieno, et al., 2003).

Dynamic NURBS (D-NURBS), as studied by Terzopoulos and Qin (Terzopoulos and Qin, 1994), incorporate mass distributions, internal deformation energies, and other physical information within the NURBS geometrical substrate. Modification of surfaces is then allowed not only by moving control points or changing weights, but also through direct manipulation of the shape as a physical entity, by applying forces and imposing constraints, according to discrete Lagrangian mechanics.

However, the most frequently used discrete technique is the *particle-based* method (Witkin, 1992), in which shapes as described by a finite number of particles with mass, having a certain position and velocity, subjected to internal and external forces and analysed through Newtonian-Lagrangian dynamics (Szeliski, Tonnesen wt al., 1993) (Provot, 1995) (Volino, Courchesne et al., 1994), or assuming certain minimum potential energies under static conditions (House, Breen, et al., 1992). Particle-based models have been extensively considered in the literature, and particularly for 2D surfaces such as cloth (e.g., (Provot, 1995) (Volino, Courchesne, et al., 1994)), as they are particularly efficient when shapes are subjected to large deformations (differently from continuous approaches), and computationally fast. The computational cost is, however, related to the finesse of the particle grid and the chosen discretization method for the associated numerical model: for Newtonian or Lagrangian particle-based shapes, in fact, an initial ODE problem has to be solved by explicit/implicit integration methods. The most classical particle-based model is the *mass-spring* model, in which the internal forces are described through elastic interactions following Hooke’s law between pairs of adjacent particles, with inclusion of possible viscous damping. However, a tricky aspect in particle-based modelling is proper evaluation of inter-particle force parameters for unstructured particle grids on anisotropic materials (Bourguignon and Cani, 2000). Current research on particle-based models particularly investigates adaptively refined particle meshes, based on subdivision techniques, as shown by Hutchinson et al. (Hutchinson, Preston, et al., 1996), McDonnell and Qin (McDonnell and Qin, 2002) for haptic applications, and in many other works.

3.3. Commercial products

All CAD systems currently on the market propose tools to generate shapes and many of them include sweeping techniques for curves. An exhaustive state of the art on surfaces generation is not really meaningful. We prefer to focus on those related to sweep and/or voxel based that will be the ones we will use in our project.

3.3.1. Sweep-based

As mentioned above the sweep commands provided by commercial CAD systems target generally mechanical engineering, they fulfil functional requests and are support generation of features such as lip, rip, and piping.

Often the generated surfaces by these sweep commands correspond to tensor product surfaces {profiles(u)⊗displacements(v)}, where the displacement is defined by other geometrical entities such as curve or curve on surface Frenet systems, more rarely they consider envelope computations i.e. the profile is a surface (two parameters) that gives Envelope [{profiles(u, w)⊗displacements(v)}].

Since it is not their main objective, no real attention is given to the aesthetic quality of the resulting shapes therefore the fine control of aesthetic properties such as isophotes, highlight or reflection lines is not really a matter of interest.

The picture below show some reflection lines red circled that for sure a stylist would accept. A pure mechanical engineering sweep rarely consider these lines as a final criterion hence cannot be used as such for industrial design market.

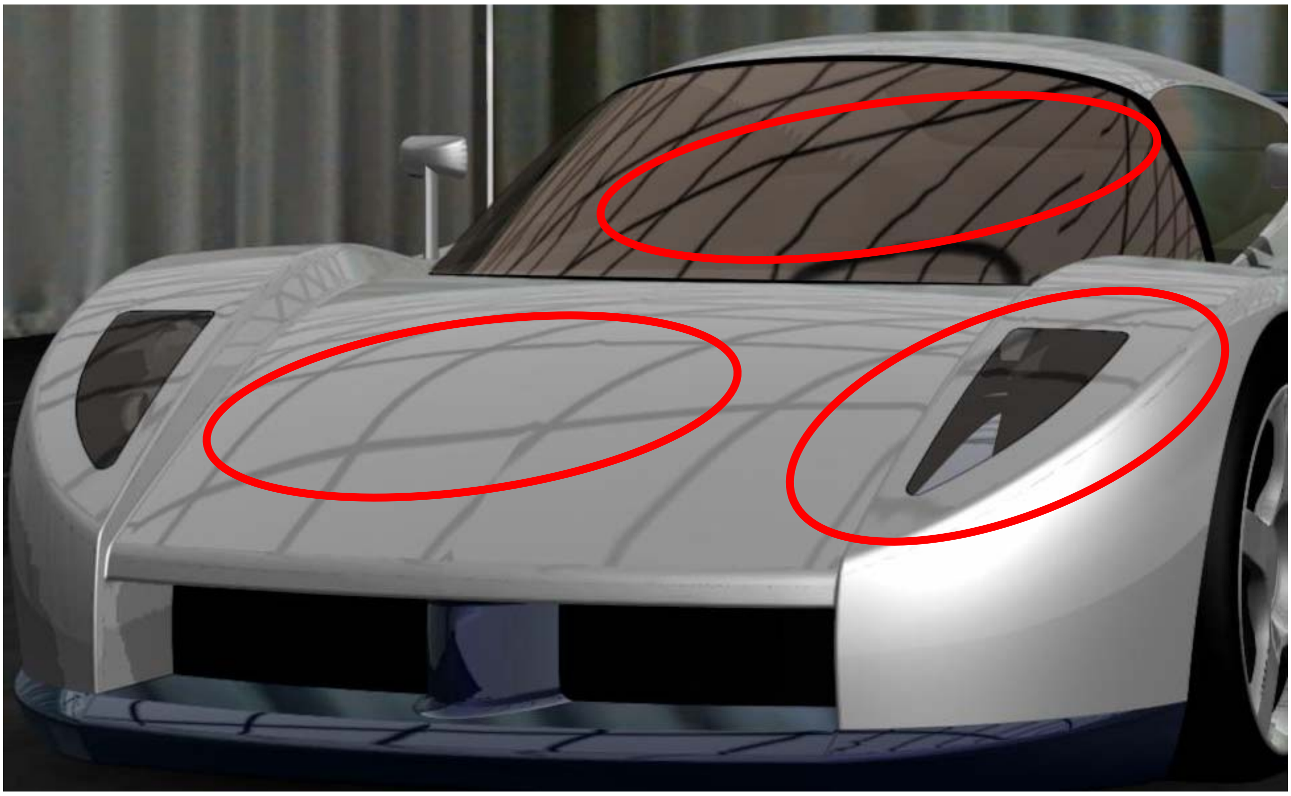

Fig. 2 –Aesthetic Properties: Reflection lines

The main apparent issue is the treatment of self-intersections and the removal of invalid parts. However regarding high quality shape, there is a more subtle issue based on the generation method itself. The internal continuity of the resulting shape is, of course, a direct function of the profiles and the "displacements" that in-turn need high order continuity almost never reached with the classical C^2-NURBS. For instance a displacement based on a curve Frenet system generates a G^0 continuous surface if the tangent and the first normal vectors of the curve are G^0. Thus the curves must be G^2 continuous, if one wants a G^1 surface then the displacements curves must be

G^3, and so on for higher continuity orders. It must be remembered that G^2 continuous shapes are a “must” for stylistic shapes.

The pictures below illustrate the continuity issue, the top pink spine curve is a C^1-NURBS, the middle blue one is a standard C^2-NURBS while the bottom green one is more than C^2-continuous. Obviously the curvature plots show that in case of a Frenet motion of the red profile without any particular caution, G^0 and G^1 discontinuities would occur except for the last bottom right picture).

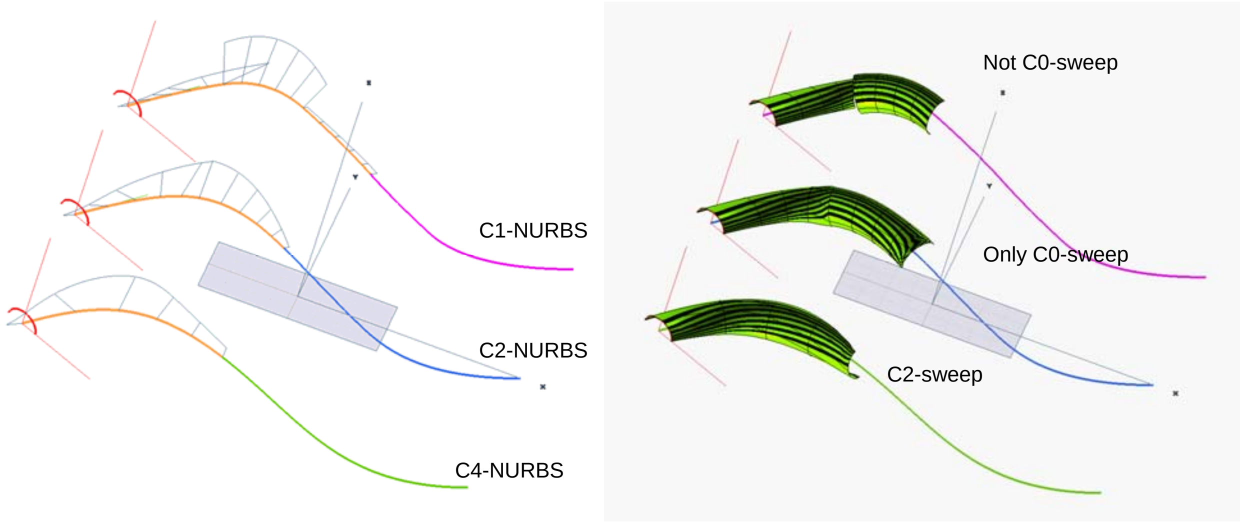

Fig. 3 - Continuity

Envelope computations allows to reduce the continuity issue but increases the self-intersection one; Moreover the explicit representation or at least a computer usable one for downstream treatment is rather complex.

3.3.2. Voxel-based

These models are mainly used as auxiliary tools for scene displays and/or for accelerating some CAD computations, as well as NC simulation. We know only one commercial CAS system based on a haptic exploitation of a voxel representations namely *Freeform* of *SensAble technologies* [http://www.sensable.com].

They wrote in one of their recent papers: ”SensAble Technologies’ Freeform is one of the rare CAD products capable of producing three-dimensional virtual prototypes of intricate products without the frustrating drawbacks of conventional solid features. Freeform is able to do this because it employs radically different software architecture. Instead of defining solid shapes by their boundaries, Freeform employs volume elements that can be sculpted like virtual clay. Freeform models don’t fail because they can’t process the requested geometry. If a shape doesn’t look right, designers can add or carve away material at any level of detail until it does.”
The above claim is correct with respect to the generation of organic shapes, the coupled haptic device simulates a spherical sculptor’s tool used to remove or add “matter” from / onto an initial block of matter. However they are providing a more classical shape generation tools, based on extrusion or rotation of profiles in order to “save time” by allowing the user to define an initial block closer to the final expected shape. This process is understandable but up to some extent it is a sign that spherical tools are not sufficient. Moreover considering their “gallery” of objects it is clear that the high aesthetic quality level required by the car industry or high-end customer products is not reached (see below the red circled areas in the pictures extracted from their site). The smoothest / fairest parts are probably those generated by the tools in order to better define the initial block.

Fig. 4 – Aesthetic quality in high-end customer products

In addition to the difficulty of reaching a large-distance high quality level with a spherical tool, the fact that the representation is quite different from all CAD systems is an obstacle for a quick deployment. As already mentioned the translation of voxels into NURBS is a tough phase that can introduce unwanted artifacts as in any surface reconstruction process (unwanted oscillations for instance).

Finally, despite the fact that *Freeform* constitutes a breakthrough from the user interface (UI) point of view, the design process is quite classical i.e. the user still generates something and then evaluates the results.

Nevertheless, we consider this technique as promising and it would be good to combine this innovative UI with a more aesthetic intent driven process.

3.4. Labs prototypes

Despite a large literature (see § *Shape modelling methods and techniques*), a look throughout current academic shape modelling prototypes still reveals a certain lack of tools for high-level interactive shape manipulation and sculpting that are sufficiently intuitive for final users, capable to enhance modellists' creativity and design potentials as concerns shape *quality*, *complexity*, *aesthetics* and *function* (Fiorentino et al, 2003).

We first briefly make some preliminary remarks on drawbacks of some recent modelling approaches, though sponsored by the scientific community, towards effective applicability to CAD/CAS systems. Then, we introduce some existing academic prototypes that will have some connection with T'nD research work.

3.4.1. Recent trends in geometric modelling tools

There are numerous publications related to shape generations. It is almost impossible to look at all of them; hence we proceeded by sampling the world wide publications. However from our regular reading of specialized CAD publications and conferences participations or reviews we have a rather good knowledge of what is on-going, and we can state that nothing really new came in within the last 10 years.

NURBS representation has been extended to spherical triangular bases (Alfeld, Neamtu et al., 1996) but the heaviness of the formalism is increasing accordingly. We doubt that this extension can be used before a while in the commercial CAS / CAD systems.

Subdivision techniques progressed but the drawbacks mentioned above are still there and will not disappear until adequate packaging in more global intent features.

Algebraic implicit formulation has been studied and applied mainly for rendering purpose but an on-going European project GAIA-II (http://www.sintef.no/static/AM/gaia/) aims at using this approach for detecting self-intersections. Algebraic implicit representations are more difficult to handle in downstream algorithms than explicit multi-parametric ones.

Despite their long history radial basis functions were not widely used in the CAS / CAD applications. Nevertheless some applications exist for curve or surface reconstructions (Laga, Piperakis et al., 2002). They require heavy computation. However recent works (Savchenko, Kojekine et al. (2003) could lead to an increasing use of this representation.

All above formalisms require a translation (approximation) to be used by standard CAS / CAD systems; it is an obstacle for a quick wider deployment. These works forget that the shape generation is only one and "simple" step of the design process. The European project FIORES-II has demonstrated that the style of an object is a social construction, hence requiring several downstream refinements after the initial generation. As a consequence the representation of this initial generation must be usable downstream and enough versatile to represent all possible shapes without limiting the designer's creativity.

3.4.2. An Academic Prototype: SoftWorld

A physics-based modelling prototype has been recently developed at the Dipartimento di Meccanica of Politecnico di Milano, named *SoftWorld* (Fontana et al. 2003). In its current release 2.0, SoftWorld is a multi-platform system for the modelling and simulation of thin deformable shapes immersed in 3D virtual scenes including rigid obstacles and supports. SoftWorld is not an animation system, but is conceived for design and simulation purposes, aiming at accurate prediction of shape behaviour depending on the component material and interactions with the environment. The considered thin shapes to be modelled are, typically, textile configurations such as tarpaulins, coverings, and apparel, or thin materials of industrial interest characterized by a highly deformable behaviour (e.g., flexible material sheets, etc.).

The underlying physical model is based on a discrete representation of deformable surfaces by structured or unstructured particle meshes in 3D space subjected to Newtonian dynamics. Internal forces are computed by estimating local spring, bending and shear effects from global experimental data measuring material properties. For textile components, for instance, the material behaviour under deformation stress is estimated by experimental data gathered from the *KES-F* system (*Kawabata Evaluation System of Fabrics*, a system for fabric hand evaluation, well-known by textile manufacturers). Interactions with an external environment are expressed as active forces (e.g. gravity, viscosity, wind), collisions against obstacles, self-collisions, and constraints. In its specialization for the textile/clothing domain, the system includes functionalities emulating the construction process of textiles and apparel, e.g., mesh sewing/assembly, insertion of small components, multi-layered fabric composition, mechanical shape deformation, 2D-to-3D mapping rules, etc.

SoftWorld's high-level architecture is shown in Figure 5. The system includes several modules that can be grouped into two fundamental stages:

- *2D/3D Modeller*, generating the physics-based model associated to 2D shapes in 3D scenes;
- *3D Simulator,* returning the dynamic simulation of the objects at discrete time steps $t_0, t_1, .., t_n$.

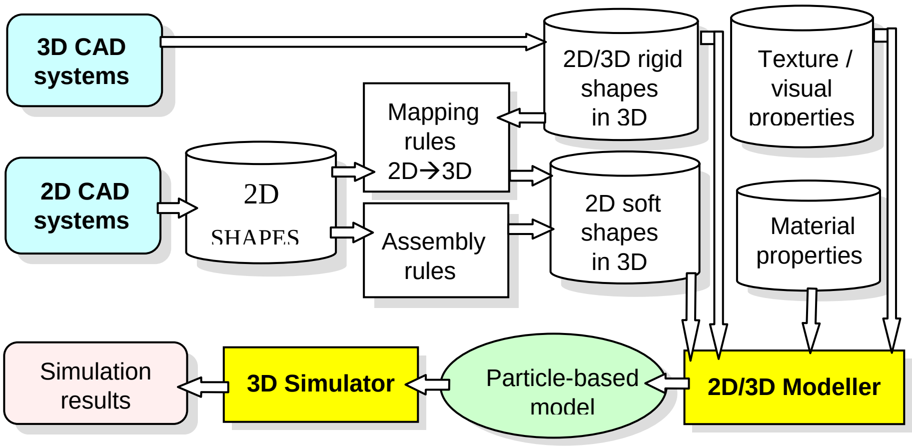

Fig. 5 – Softworld's high-level architecture

A graphical user interface is under development, from which the main system's modelling and simulation phases can be executed in a unique environment. The main GUI's functionalities include tools for geometric modelling, particle-based modelling, dynamic simulation and post-processing analysis, import/export of graphical file formats, image/video generation.

Extension of SoftWorld to full 3D modelling/simulation capabilities in currently under investigation, according to a two-fold intent: 1) non-real time simulation with accurate collision detection and 2) real-time simplification for haptic rendering applications (Cugini et al., 1999) (see § *Haptic technology update*).

As concerns the non-real time SoftWorld project, extended with 3D physics-based modelling tools, a broad high-level input data structure for the 2D/3D Modeller is characterized by the following information:

- databases about materials with information about mass density, deformation behaviour under stress, friction, etc. (e.g., data in KES-F format for fabrics, and other formats related to other 2D/3D material categories);
- 2D/3D geometries of shapes with the role of rigid bodies (e.g., mannequins, frames);
- geometry of 2D shapes, in 2D, having the role of deformable surfaces (e.g., textile patterns);
- (for 2D soft shapes) corresponding rules for 2D→3D mapping;
- geometry of 3D shapes having the role of deformable 3D objects (e.g., sponges, packs, etc.);
- further model's assembly/construction constraints depending on the domain (e.g. for the textile domain: seams/darts, layers, buttons);
- (when existing) dynamic constraints (imposed conditions, as well as kinematics of possible rigid parts in motion).

Output data returned by the 2D/3D Modeller correspond to input data for the 3D Simulator, i.e.:

- physical information about particle systems associated to soft shapes/materials:
  - 3D positions of particles,
  - particle masses,
  - associated grid (list of connections between particles, list of triangles),
  - internal forces (bending, traction/compression, shear interactions),
  - external forces (gravitation, viscosity, wind, constant applied forces, etc.),
  - geometrical/kinematic constraints (fixed particle positions, fixed particle trajectories, constant distances between particles, area conservation, etc.);
- geometric/kinematic information about triangulated surfaces describing rigid parts (up to now, SoftWorld does not include yet rigid body dynamics):
  - 3D points,
  - associated grid (list of connections between particles, list of triangles),
  - geometrical/kinematic constraints (fixed positions for points, fixed trajectories, constant distances between points, area conservation, etc.).

Based on constrained Newtonian dynamics for particle systems, supported with collision management at each time step of the chosen time discretization scheme ((Cugini et al., 1999) (Fontana et al., 2004) and references quoted therein), the 3D Simulator returns as output data physical information at discrete time steps $t_0, t_1, .., t_n$ describing:

- configurations $\{\mathbf{r}_i(t_k)\}$ for each particle $i=1,2,..,N$, for time steps $k=1,2,..,n$;
- velocities $\{\mathbf{v}_i(t_k)\}$ for each $i=1,2,..,N$, for $k=1,2,..,n$;
- other information: forces, energies, etc.

Though an academic prototype still under improvement/extension, the system has been already experimented in the framework of several European and national projects, such as the Brite-Euram projects *DMU-FS* (*Digital Mock up for Functional Simulation,* with several partners from the automotive industry; see www.samtech.fr/links/partners/dmu-fs/dmufs.html) and *MASCOT* (*Intelligent 3D Design and Simulation System for the Clothing Industry*, in collaboration with CAD/CAM developers and clothing companies; see www.univ-valenciennes.fr/sp/mascot/), and the national projects *TA2000* (*Consorzio Tessuti/Abbigliamento 2000*, with CAD and clothing companies) and *Vi-DreR* (*Virtual Dressing Room*) (Fontana et al., 2004). As applications, several cases of shapes for the textile domain have been considered, such as garment models (men's jackets, etc.) for the clothing sector, or functional textiles used in the automotive industry (e.g., soft car tops), as shown in Figure 6.

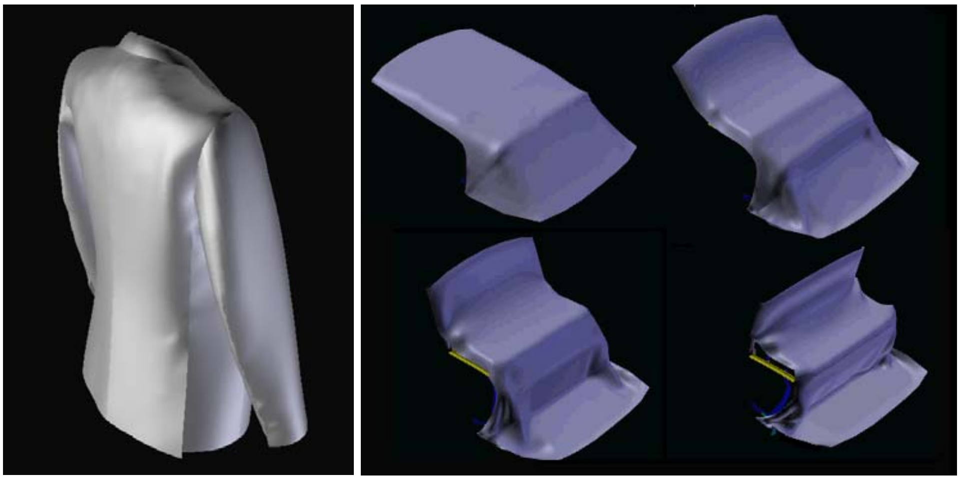

Fig. 6 - SoftWorld: simulation of shapes for industrial applications (garments, sunroofs)

3.5. Future and emerging methods

Considering the last remark in § 3.4.1, we think that such a versatile representation should be very basic to be easily usable. Very probably the representations are too sophisticated to be robust enough versus the way the “real numbers” are represented in the computers. It might happen for CAS / CAD data what happened for music and cinema i.e. unification via the digital representation.
In our case, the voxel-based approach could become the future provided that discrete constructive constrained geometry theory would be developed. It is not an emerging method since the first commercial CAD solid system (Euclid from MATRA DATAVISION in 1979) was based on tessellated representation, but the fact that it can indeed be considered as a possible future (GEOMETRICA, 2003) (Discrete geometry).

The challenge is to define the right theory that will allow discrete schemes to support high quality shape generation, i.e. what is a discrete tangency or curvature or higher continuity, etc.
In the meantime we have to cope with a hybrid representation to allow us the mandatory treatments that come after the shape generation. It is what we plan to do within our project.

3.6. Benchmarking of current technology suitable for T’nD

So far, after the state of the art survey our initial intent is not changed. We will study the T’nD shape generation as a four-step process:

1. The user's haptic based motion that should be supported by a voxel model for flexibility reason.
2. The recognition / identification of a closest generic sweep method for final quality control.
3. The NURBS formatting for downstream treatment.
4. The haptic based modification / refinement global or local of the generated shape(s).

Note that steps 3 and 4 can be performed in either order.
In addition to the technical difficulties that we foresee (see § 3.7), it will be impossible to implement a complete system in the time frame of T’nD but for each step a subset of this general process will be implemented.

Currently we have at our disposal *think3* tools to:

- Generate shape under basic motion i.e. given variable profile $\mathbf{P}(u, t)$ and a motion $\mathbf{M}(t)$, we get the shape $\mathbf{S}(u, t) = \mathbf{P}(u, t) \otimes \mathbf{M}(t)$. Several years of development in cooperation with a large Japanese car manufacturer company led us to understand what can be expected from sweep generations regarding high quality aesthetic shapes. We will have to identify one or two meaningful motions used in the shop floor by the modellers when scrapping the clay with shaped templates.
- Approximate any n-dimensional function of one or two variables by a NURBS with C^k – G^k boundary constraints. It is a versatile component largely used in *thinkdesign* product that allows us to face the mandatory translation of any representation into a NURBS one thus decreasing the impact of the drawback of being not accepted by CAS / CAS standard systems.
- Check if any self-intersection exists in a NURBS surface. Based on an effective numerical algorithm this component allows a real time treatment of a reasonably complex shape. It is a result of GAIA-II project. We will discuss its availability for our project in the frame of AIM@SHAPE, the Network of Excellence with which we are in relations. This tool could become important to avoid generating invalid shapes.
- Trim any geometric entity and to glue it into a B-rep. This could be valuable for the removal of unwanted / invalid parts of envelops.
- Modify precisely any B-rep based shape under various constraints while preserving its internal continuity. Based on a morphing driven by energy-like optimization, this *think3*

component, released in 2000, has been **unmatched until now** in the industrial market. Other morphing techniques are also available. They will be used as a support of the modification step.

Moreover we have some experience in:

- Envelope computations, especially for developable surface used in drafting processes or for the parting "plane" generation both particularly useful in the mould industry. However we must recognize that despite we were in quite simple cases of plane and conic surface envelops, their implementation was difficult. This let us suppose tough periods in the next steps of the project.

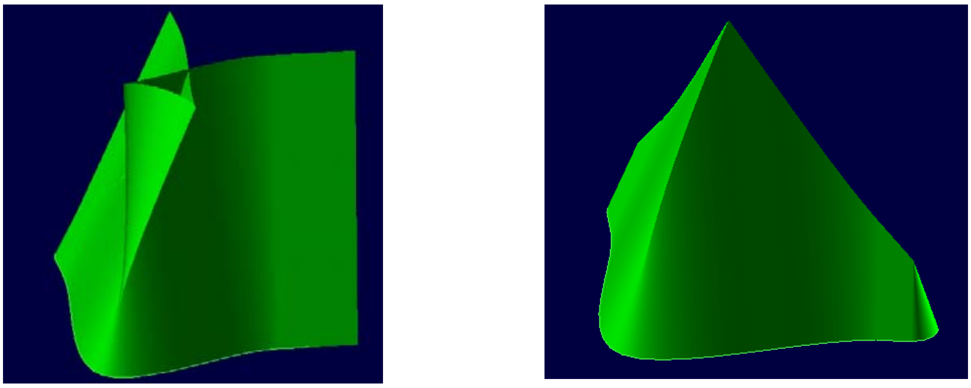

Fig. 7 – think3 treatment of envelopes

The pictures above show how *think3* treat envelopes. It is the envelope of a plane moving along the bottom curve tangent to it and making a constant angle with the "vertical" (in the picture). On the left the self-intersection is kept while on the right the unwanted part has been removed.

- Facing the subtle drawback due to piecewise character evoked in § *Sweep-based.* The upcoming (May 2004) version of think3 product will provide stylists with a blending of shapes that numerically overcomes this issue. The method is to propose quasi-continuity almost everywhere except at some singular points. The above mentioned approximation components are used here to control the quality of the quasi-continuity.

3.7. Critical issues related to T'nD technology

At this stage of the project the issues related to the shape generation we foresee (independently of the other parts) are mainly concentrated in the steps #2 and #3 of the four step process presented in the previous §.section. They are:

- The explicit representation of envelops. Provided that the motion is given (recognized and identified), envelope of the shaped template will be given by a set of equations between which we will have to eliminate some parameters. For instance if the motion depends on a single parameter t and the shaped profile is not deformable and defined as a surface of two parameters {u, v} then the envelope is given by:

  $\mathbf{S}(u, v, t) = \mathbf{P}(u, v)\otimes\mathbf{M}(t)$ and, noting $\partial_x\mathbf{S}$ the partial derivative of S versus the variable x,

  $\text{Determinant}(\partial_u\mathbf{S}, \partial_v\mathbf{S}, \partial_t\mathbf{S}) = 0$ which links the parameters u, v, t thus inducing a "surface".

  We might face more complex cases where the motion depends on several parameters {t1, t2, …, tm} and the shaped profile can vary as a function of a [subset] of these parameters.

  $\mathbf{S}(u, v, t_1, t_2, \dots t_m) = \mathbf{P}(u, v, t_1, t_2, \dots t_m)\otimes\mathbf{M}(t_1, t_2, \dots t_m)$ and

  $\text{Determinant}(\partial_u\mathbf{S}, \partial_v\mathbf{S}, \partial_{tk}\mathbf{S}) = 0$ with k = 1, … m that gives m equations to link the parameters thus again inducing a "surface".

However we will try to avoid these complex cases especially because the expression of the motion itself can be subject to the resolution of implicit equations (constrained motion). Hence we will focus on simple cases first and then will approach if we have time the variable profile a function of the motion parameter i.e. by increasing order of difficulty:

$\mathbf{S}(u, t) = \mathbf{P}(u)\otimes\mathbf{M}(t)$	Simple motion of a non deformable profile **P** without thickness.
$\mathbf{S}(u, t) = \mathbf{P}(u, t)\otimes\mathbf{M}(t)$	Motion of a deformable profile **P** without thickness.
$\mathbf{S}(u, v, t) = \mathbf{P}(u, v)\otimes\mathbf{M}(t)$	Motion of a profile **P** with thickness.
$\mathbf{S}(u, v, t) = \mathbf{P}(u, v, t)\otimes\mathbf{M}(t)$	Motion of a deformable profile **P** with thickness.

With these case our experience in sweep generation let us expecting a rather good coverage of possibility. Nevertheless we are not sure to treat all of them in the project time frame. The works referenced in (Abdel-Malek, Blackmore e al., 2004) will give us some suggestions but we foresee that we will have to build our own numerical method.

- The external and internal continuities. Here we will face the subtle drawback of piecewise define geometry. Shaped profiles and the Motions will have to be enough continuous to provide a good quality of the resulting shape. A workaround might be to use large C-infinite continuous geometry as input of motions or profile definition. However we will not forget this issue since the duration of life of entities of such kind of entities in CAS / CAS system is very short.
- The self-intersection detection and removal of invalid / unwanted parts. Considering the shapes that we will have to generate, self-intersection should not occur. As a matter of fact it is rare that the stylist wants a real sharp edge. Hence we will have just to detect and warn if such a case occurs. Regarding the removal of invalid parts, we will probably face some difficulties to find the boundaries of the valid domains i.e. the trimming curves.
- The aesthetic intent driven process. It covers the choice of some motions that are used by the modellers in the workshop. It is not a real issue in the technical sense but it is mandatory to select the right ones, a few but meaningful enough to make the users comfortable. Also user’s behaviour regarding self intersection should be taken into account.
- Regarding the modification we don’t expect many or big issues. The “only” CAGD problem we foresee will be translating into *think3* modification engine constraints some user’s gestures.

3.8. Conclusions

The system we intend to develop aims at providing a natural way to generate smooth shapes and to modify them. The generation mode will be based on envelope computations of virtual tool motions (thick shaped templates) simulating the modeller’s work in the shop floor. The results will be directly usable in classical CAD systems. This is where the most critical issues of the shape generation stand. The modification mode will be based on the modification tools available via think3 partner. They will be improved and adapted to the time frame required for the haptic device.

Both modes will lead to a subtle integration of envelope computations, voxel modelling in the real time phase, tools for surface deformation, particle based approach and volume modelling. Considering the state of the art, the project will constitute leap ahead that will also have several side effects in CAGD.

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4. Cognitive ergonomics update

4.1. Introduction

Cognitive ergonomics plays an important role in the design and future development of the TnD system, since it aims at bringing *the "point of view of the user"* in this project, in order to have a user-oriented system (see Norman, 1993, 2002). Indeed, new systems intended to allow Human-Computer interactions have to be *both useful and usable*. The utility concerns whether the functionality of the system can do what is needed and the usability concerns the quality of the interaction when the user attemps to make use of the system's functionality.

The success of a computational system, whatever it is, is not only dependent on its technical developments. It also depends on its capacity to satisfy the users' needs and competences. Therefore, the *usability* appears to be a main condition in the success of a project (see, for instance, Nielsen, 1993, 2000; Nogier, 2003). Delays or even failures in the development of systems are often due to a lack of knowledge of what will be the effective use of the final system, which leads to first versions of the systems that are badly adapted to the users' needs and to their context of use. In such cases, adjustments and new developments have to be performed, requiring unplanned expenses. Otherwise, the systems will lead to important cognitive difficulties of the users, errors that may be dangerous for them and their environment, and finally difficult acceptation or even rejection of the system.

Therefore, the design of new systems, whatever they are haptic or more classical, requires satisfying the major criterion of usability. Several definitions of usability have been proposed, but we choose a recent one: "the capacity of the object or system to be easily used by a given person in order to perform the task for which this object has been designed and developed" (translation from Nogier, 2003, p. viii).

This notion of usability refers to both:
- the system's performance for performing the task,
- the user's satisfaction when using this system,
- the ease to learn of to use it.

When used in a professional area, the usability of a system is essential since the performance of users will depend on it. A system that is easily usable will allow performing quickly the planned task, without lack of time and with less stress. Thus, for companies, the usability determines both the productivity and the quality of work conditions for professionals (see Meyer & Seagull, 1996; Hendrick, 1997).

In order to contribute to the usability aspects of the Tn'D system, in the following sections, we present the main theoretical foundations related to the context of use of this future system. Especially, we adopt a cognitive point of view for characterizing design activities as well as gesture and treatment of haptic information. Then, on these bases, we point out the interest and limits of classical ergonomics principles and criteria for both developing and assessing the Tn'D system.

4.2. From cognitive psychology to cognitive ergonomics

4.2.1. Findings about design activities

From a cognitive psychology point of view, design activities present several important characteristics (see, for instance, Bonnardel, Lanzone & Sumner, 2003).

Problem-solving activities

Design activities are described as problem-solving activities: designers have to define a product which should fit a specific function and satisfy different requirements - this defines to some extent the "goal" to reach - but the designers cannot directly apply pre-defined procedures to reach this goal (cf. Malhotra, Thomas, Carroll & Miller, 1980).

Ill structured and open-ended problems, and co-evolution of problem and solution

Design problems are particularly complex since they are both *ill structured and open-ended*. Design problems are considered *ill structured* because designers have, initially, only an incomplete and imprecise mental representation of the design goals (Reitman, 1964; Eastman, 1969; Simon, 1973). The designers' mental representation evolves as the problem-solving progresses. Thus, Cross & Dorst (1999) described the *co-evolution of the problem and the solution*: the designer formulates a partial structuring of the problem-space and then transfers that partial structure into the solution-space, and so develops both problem and solution in parallel. Converse cases were also described, in which solution-structuring preceded problem-structuring: the designer first identifies a partial structure in the solution space (e.g., a preferred shape, or form) and uses that to structure the problem-space. These two variant strategies of co-evolution are in line with the description of an iterative dialectic between *problem-framing and problem-solving* (Rittel & Webber, 1984; Simon, 1995). During problem-framing or problem-structuring, designers refine design goals and specifications and, thus, refine their mental representation of the problem. During problem-solving, designers elaborate solutions and evaluate these solutions with respect to various criteria and constraints, which guide the designers in performing subsequent stages of design problem-solving (Bonnardel, 1993, 1999). As previously pointed out these processes are intertwined and this dynamics leads each designer to progressively construct his or her own representation of the design problem and, therefore, to deal with a problem that has become specific to him or her.

Design problems are also considered *open-ended,* since there is usually no single correct solution or direct procedure for a given problem. There is instead a variety of potential solutions, which satisfy different criteria or constraints to varying degrees. Thus, different designers, supposedly solving the same design problem, reach different solutions, all of which may be potentially acceptable (Bisseret, Figeac-Létang & Falzon, 1988). Moreover, the criteria and constraints used during design are also open-ended (Bonnardel, 1999). They are not completely dependent on explicitly stated design requirements. New ones are constructed to reflect the designer's evolving mental representation of the design problem and his or her own point of view (Bonnardel, 1993). These constructed criteria and constraints can depend on the designer's prior design experiences, personal preferences, and his or her understanding of other stakeholders' concerns (Bonnardel & Chevalier, 1999; Martin, Détienne & Lavigne, 2001). In addition, it was argued that such criteria and constraints play an important role in designers' creativity, together with analogy-making (Bonnardel, 2000): depending on the nature of sources of inspiration, analogy-making could extend the space of research of new ideas, whereas criteria and constraints would guide and control the research process.

Opportunistic process

The dialectic process between problem-framing and problem-solving contributes to another characteristic of design problem-solving: it is viewed as an *opportunistic process*. Several years ago, much debate centred on whether design activities were hierarchically organized (see, for instance, Jeffries, Turner, Polson & Atwood, 1981; Adelson & Soloway, 1985) or opportunistically organized (for a review, see Visser, 1994). The seminal study of Hayes-Roth and Hayes-Roth (1979) and later research (see, for instance, Bisseret, Figeac-Létang & Falzon, 1988; Guindon, 1990; Visser, 1990) provided arguments on behalf of an opportunistic organization of design activities, though they possibly include hierarchical episodes. The design process was thus described as multi-directional: decisions included both top-down and bottom-up instances and they could be made at different levels of abstraction, etc. Such an activity was characterized by the authors as opportunistic because "each decision [was] motivated by one or two immediately preceding decisions, rather than by some high-level executive program" (Hayes-Roth & Hayes-Roth, 1979, p. 381). Such decisions could lead to reconsidering previous decisions or postponing certain decisions (Hayes-Roth & Hayes-Roth, ibid., Visser, 1990; Bonnardel, Lanzone & Sumner, 2003).

Externalizing process

The externalizing process consists in causing state changes in an external representation, which result in a different 'what you see' (Nakakoji & Yamamoto, 2003, p. 1258) and, thus, contributes to explain the opportunistic process observed in designers' reasoning as well as their creativity.
Numerous studies stressed the importance of externalizations for human cognition. For instance, Scaife & Rogers (1996) proposed the notion of external cognition to emphasize the importance of graphical representations in helping human cognition.

Concerning the *externalizing process* itself, Schoen (1983) argued that *reflection-in-action* is an important aspect of the design activity. A typical example of the act of externalizing is sketching. Schoen (ibid.) distinguishes between reflection-*in*-action and reflection-*on*-action and points out the fact that for a designer, moving his/her hand while drawing sketches is crucial in the reflective thinking. In this sense, externalizing can be viewed as helping the construction of mental imagery and affecting what the person thinks, feels, knows and understands (Nakakoji & Yamamoto, 2003). Thus, the externalizing process interacts with designers' cognitive processes in order to contribute to the identification of problems by designers, the formulation of solution spaces, and the adoption of new points of view and exerts an influence on extending the boundary of the initial solution space (Bonnardel & Marmèche, 2001).

4.2.2. Findings about cognitive treatment of haptic information

The haptic system is:

- A perceptive system, with several modes;
- An effector or action system.

The perceptive system associates in a rather complex way

- Touch, based on cutaneous (embedded in the skin) mechanoreceptors (receptors of mechanical stimulation or forces)
- Proprioception, providing a sense of position and motion, or kinaesthesia, based in mechanoreceptors located in the muscles, tendons and joints.

To put it rather broadly, touch brings in information about the external world (Klatzky 1993):

- Temperature
- Textures
- Hardness or compliance
- Weight
- Shapes.

As an effector, the haptic system not only produces output in the form of actions, but also contributes information, by helping the fingers, and the hand in their exploration of the surfaces, shapes, and distances. Furthermore, through muscular proprioception, it provides information upon the shape of large objects, and upon the situation of the body in space, and its relation to the surroundings objects in the environment.

Constant feedback between the perceptive input, relative to both the environment and the motions performed for exploration and/or action, and the motions performed for controlling and adjusting the motor behaviour during the progress of action are co-ordinated centrally. Such central co-ordination and integration are the basis for the building of motor program memory base or repertoire. Motor skills are a measure of the extension of this repertoire and of the capability of the person to exploit this repertoire for performing actions oriented toward a goal.

The perception provided by the haptic systems is rather widely explored and documented, mainly thanks to the research of Roberta L. Klatzky and Susan J. Lederman. The two authors recently completed a survey of the large theoretical and empirical literature (Klatzky, 2002), which could be usefully consulted. Two recent books complement and update this study (Hatwell, 2002), Hatwell 2003). Here, only main research results relevant to the present T'nD project will be pointed out.

Texture

Perception of roughness is primarily based upon differences in deformation of the skin resulting from changes in groove depth and width on the surface explored. The active exploration by fingers moving over the surface is relatively independent of the motion speed, suggesting that kinaesthesia plays a minimal role, while the manner in which the skin is deformed is critical (Conor 1990).

Taylor and Lederman (Taylor 1975) presented a model of perceived roughness based on a mechanical analysis of the skin deformation according to fingertip force, groove and ridge width.

Weight

The perception of heaviness results from several factors, such as:

- The object being wielded or only resting;
- The rotational forces imposed on the limbs;
- The material from which the object is made (Ellis 1999);
- The way it is gripped.

Perception is furthermore affected by some distorting factors, such the relation between size and weight: a small object is perceived heavier than a bigger one of same objective weight (Amazeen 1996), (Gentaz 1998).

Actually, the interactions between weight perception and the motor command of the grip appears rather complex: it has been shown that weight perception is affected by the width of the grip, the number of fingers involved, and the contact area, but not the angle of contacted surfaces (Flanagan 2000).

Curvature

Curvature perception is subject to error from various sources (Pont 1998). One factor is whether the exploration is static or dynamic (Davidson 1974), (Pont 1999).
Among other factors are:

- The surface previously touched prior to the exploration (Vogels 1996);
- Curvature orientation with respect to the exploring finger (along or across the finger) (Pont 1998);
- Region of contact with the hand (palm or upper surface) (Pont 1997).

Role of manual exploration

Several different types of gesture are used in order to seek different properties of objects (Lederman 1987):

- Lateral motion for texture;
- Static contact for temperature;
- Enclosure for volume and shape;
- Pressure for compliance;
- Unsupported holding for weight;
- Contour following with one or more fingertips along edges or surface contour.

Another method of exploration is wielding the object in one's hand, instead of letting the hand rest on the object, or passing over it. The inertia of the object is used to evaluate heaviness, but also some geometrical properties of the object (Turvey 1995), (Turvey 1996).

Haptic space perception

The representation of space, resulting from haptic exploration out of the control of vision, is not uniform, and not submitted to one single metric. In other words, haptic spatial perception is anisotropic. Paradoxically, this may be considered as evidence for the cognitive status of the integration of haptic sensory information: “high-level cognitive processes mediate the linkages between motor exploration, cutaneous and kinaesthetic sensory responses, and spatial representation” ((Klatzky 2002), p. 17).

Perception of three-dimensional objects

As shown by Lakatos and Marks’ study (Lakatos 1999) when subjects explore 3-D objects, they emphasise the local features or the global form: Local features have a greater salience in early processing, with global features becoming more equal in salience as processing time increased. The task was to make similarity judgements of unfamiliar geometric forms (e.g., cube; column) which contained distinctive local features such as grooves and spikes. Objects with different local features, but similar in overall shape, were judged less similar when explored haptically than when vision was available. Longer exposure time (increasing from 1 s to 16 s) produced greater similarity ratings for objects that were locally different but globally similar, indicating the increasing salience for global shape over time.

Haptic memory

While there is a very large corpus of research relative to memory of verbal or graphic material, there are rather few studies concerned with memory of haptic perception. However, what will be presented below under the terms of motor programs and morphokinesis exhibit extremely long lasting memory.

4.2.3. Findings about cognitive treatment of gesture in design activities

Motor programs as a knowledge base

The control of motor behaviour, which guides the movement on the basis of both the internal and external perceptive feedback, is decidedly cognitive in nature.

Functional acts are generally planned in advance, using sensory guidance along with cognitive intention and memory for past actions. Generally, we know what action we intend to perform with an object well before we reach for it. Vision provides us with immediate and ongoing information about the geometry of action space: Where the object is and how its points of contact are oriented with respect to our body. Purposive actions with objects require that parameters relating to functional action, spatial geometry, and object properties, are converted into motor parameters, such as arm velocity, reach direction and extent, hand shape, wrist orientation, grip force, and lift force. When they are planned in advance (cf. reflexive actions), these motor parameters constitute a *forward model* of the action, designating how it will unfold over time (Fleming 2002).

However, the idea of a motor program corresponding to every motion should not be considered. A forward model or a motor program is something quite large or general, for a category of action, and such programs are to be combined into generalised motor programs (PMG) with “floating parameters” which values are specified:

- Overall duration of the motion;
- Selection of group of joints and muscles;
- Apertures of joints;
- Intensity of contraction (Cadopi, 1980, 1992).

Motor programs are not purely automatic behaviours. Rather, they consists of muscular activation instructions, always to be parameterized according to local and momentary information, coming from the various senses, particularly touch and kinaesthesia, participating in the execution of the motion, under the supervision of sight (Paillard 1984). Motor programs are selected as the motion progresses.

Of particular interest in this respect is what Paillard termed “oriented morphokinesis” (Paillard 1986): Motions with a given trajectory, in a determined portion of space, a given space and a fixed end-point or goal, or, more generally, morphokinesis are motions with a determined shape, such as the motions of the dancer, the writer, or the draftsman. Control of the shape and size of the motion during the performance are necessarily, however automated the motion, under some degree of cognitive control.

By stimulating with 10 to 100 Hz vibrations the muscular captors, it is possible to produce illusory motion sensations, corresponding to the perception that would have been generated by actual motion (Roll 2000). “Such kinaesthetic sensations constitute actual *motor shapes*” ((Roll 2003), p.56). Applying such stimulation to the hand, elbow and shoulder, it has been possible to suggest to the subject the feeling that he or she is drawing specific shapes or writing figures and letters. Roll concludes the following: “Le fait que la manipulation par vibration de la sensibilité musculaire au niveau de la main donne naissance à la perception de *mouvements virtuels symboliques* identifiés et reconnus par le sujet, suggère que la sensibilité musculaire dans son ensemble participe *à des fonctions mentales de niveau élevé,* fonctions qui relèvent clairement du champ des *activités cognitives.*” (p. 59).

Drawing and handwriting are clear examples of morphokinesis. Since the early 1980s, they are studied under the heading of "graphonomics", which according to a recent survey of the literature (Meulenbroek 2003), is “the multi-disciplinary scientific effort involved in identifying lawful relationships between the planning and generation of drawing and handwriting movements and in defining the nature and limitations of the processes taking place at various levels of the neuromotor system as these movements evolve.", p. 131.

Early studies of drawing and handwriting movements (Van Galen 1980), were mostly restricted to analyses of latencies and performance errors as a function of task-complexity variations. Recent research exploits sophisticated analyses of the kinematics, kinetics and dynamics of drawing and handwriting movements. As far as we know, studies of this kind, relative to solid modelling are certainly few, assuming there is any. We can only suggest in this respect the neologism “glyptonomics”.

The model suggested by Van Galen for writing and drawing is quite consistent with the concept of morphokinesis. Graphic activity is viewed as a two-stage process:

- A centred stage, during which a motor pattern, or program is selected from a dynamic motor long term memory, fitting with an abstract representation of the shape to be produced;
- An external stage, during which muscular parameters are selected, adapted and corrected for the ongoing performance.

The notion of knowledge management can help in building a model of the activity of the writer and the draftsman, as well as that of the dancer or any other performer of skilled motions and gestures. The knowledge base is made of motor programs for morphokinesis, learned through the training and professional practice of the performer. Experts have a larger knowledge base than the newcomers. Furthermore they have more experience, and accordingly more skill in managing their knowledge base, that is in:

- Selecting appropriate programs
- Supervising the execution of the program
- Adjusting the choice of programs to the ongoing performance

Finally they have also more experience in the control of the process. That is they can better rely upon automatic performance, while mastering emergency situations by reverting to non-automatic or conscious control of actions.

Cognitive benefits from haptic activity in design

Not only motion performance could be viewed as a form of knowledge management, it should also be viewed as an help to cognitive activity, as evidenced by a series of research upon motor activity as an help to perception, memory and reasoning in space and mechanics problems (Bellan and Poitou 2000), (Gloton 1996, 1999), (Logerais, Bellan et al. 2001), (Poitou 2001). The main conclusions from these studies are:

- In a task of perception and memorisation of two-dimensional (2D) curved shapes, when the objects become complex, the subject cannot rely upon visual cues alone, and the adjunction of kinaesthetic cues is needed.

- Mental representations of shapes result in better recognition performance when elaborated jointly with the help of vision and kinaesthesia, than with vision alone. In the former case, mental representations are build up more slowly than in the later, but are however more reliable, and stay available longer in memory.
- When the subject is asked to follow the outline of a shape displayed on a computer screen, with finger and eye motions, the corresponding mental representation is improved, as compared with a task of purely visual exploration.
- The performance is even better, when the subject mentally rehearses the outlining before actually performing it.

Other studies show that manipulation and motion improve the understanding of the kinematics of a complex mechanical object. The kinematics of a robot arm is better understood when the arm is manipulated, than when observed merely visually (Cartonnet 1992).

HCI requiring rather complex hand motions have been compared with others, less demanding in that respect, and with mere sight.

- Actually, using SpaceBall, a 3-D mouse, in the exploration of complex solid models displayed on a computer screen, resulted in shorter exploration time for the same level of performance.
- In a recognition task of solid models, displayed on a screen, performances proved better when a 2D (mouse) or a 3D (MicroScribe) interface was associated with vision, than when vision alone was used for exploring the models.

It might thus be stated that the hand, through haptic kinaesthesia, performs not only a perception/execution role, but contribute cognitively to the understanding of spatial relationships and to the planning of complex tasks.

Such results are clearly in favor of designing computer aided system for modelling in design which would rely upon the professional gestures of the designers and modelers as the language of command.

4.2.4. Ergonomics principles and criteria for externalizing tools

As pointed out previously, the acceptance of a system depends not only on its perceived utility but highly on its usability. In addition to the understanding of designers' activities with regard to the aspects described above, ergonomics principles and criteria sound useful for both developing and assessing the T'nD system.

The cognitive ergonomics literature provides:

- series of general orientations or ergonomics criteria for the design and assessing of user interfaces,
- a more restricted range of specific data, available for the design of externalizing tools.

With respect to the former point, for years, series of ergonomics criteria, principles or guidelines have been proposed by numerous authors (Carroll & Rosson, 1992; Coutaz, 1990; Helander, 1988; Holcoomb & Tharp, 1991; Nielsen, 1993; Nielsen & Molich, 1990, 1994; Polson & Lewis, 1990; Scapin, 1986; Scapin & Bastien, 1997; Neiderman, 1986; Smith et al, 1982; Valentin & Lucongsang, 1987).

Especially, the Ergonomics Criteria proposed by Scapin & Bastien (1997) fall under the following headings:

- Guidance, which refers to the means available to advice, orients, informs, instruct and guide the users throughout their interactions with the system.Workload, which concerns all interface elements that play a role in the reduction of the users' perceptual or cognitive load.Explicit control, which concerns both the system processing of the explicit user actions and the control users have on the processing of their actions by the system.Adaptability, which refers to the system capacity to behave contextually and according to the users' needs and preferences.
- Error management, which refers to the means available to prevent or reduce errors and to recover from them when they occur.Consistency, which refers to the way interface design

choices (naming, formats, procedures…) are maintained in similar contexts, and are different when applied to different contexts.Meaningfulness of codes, which qualifies the relationship between a term and/or a sign and its reference.Compatibility, which refers to the match between users' characteristics (memory, perceptions, customs, skills, age, expectations…), task characteristics and the organization of the output, input, and dialogue for a given application.Such ergonomics criteria can play the role of general objectives and can be complemented with orientations specific to externalizing systems, such as the T'nD system. Recently, Nakakoji & Yamamoto (2003) argued that we must be primary concerned with how the designer interacts with the tool and through what representations. In particular, based on an analysis of existing systems which aim at supporting externalizing, these authors point out aspects that are important to consider:

- Representational immediateness, which refers to the immediate or more distant representational mapping of what the user acts to what the system shows as a result of externalizing.
- Spatial immediateness, which refers to the fact that the user's action takes place at the same place or at a different place than the resulting externalization.
- Temporal immediateness, which depends on both algorithmic constraints and computational power.
- Realism toward domain, which refers to the fact that externalizing systems can produce representations that are closer to the domain the user is engaged than representations resulting from the user's hand-drawing. Thus, by focusing on a particular domain, such systems could map a user's simple action to complex domain objects, allowing the user to have the situation talks back to them more grounded in the domain.

Moreover, new aspects to take into consideration will result from the analyses of designers' activities, needs and wishes that will be conducted in the specific contexts of design involved in the T'nD project.

4.3. Conclusions

The foregoing state of the art gives sound indication that the cognitive ergonomics and psychological experimental literature provides:

- with respect to the designers' cognitive functioning, knowledge about the relationships between problem-framing (or problem-structuring) and problem-solving, as well as about the importance of the externalizing process in the design problem-solving;
- with respect to haptic perception, it provides a large body of knowledge accumulated during the last twenty years;
- with respect to haptic effectuation, the literature is much more restricted;
- concerning more precisely design activities, there is, under the heading of graphonomics, a large body of literature (including general recent surveys) relative to graphics, both drawing and writing;
- however, no such data base and information is available to plastic activities, such as modeling.

In addition, we pointed out the fact that usual ergonomics criteria and principles will be complemented by new aspects, which will be derived from analyses of the designers' activities and cognitive processes. Thus, based on a logical path from cognitive psychology to cognitive ergonomics, new orientations will be defined in order to fit specificities of both haptic device and of the design areas chosen for the T'nD project.

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5. Integration activities

Some ongoing research works integrate haptic interaction with modeling tools. Most of these works carried out in universities' labs. Several applications have been developed for the medical field, where haptic devices (mainly ad hoc systems) have been integrated to applications allowing for the interaction with geometric models of human body parts and tissues. Some references to web sites describing these applications are the following:
http://www.haptics.me.jhu.edu/IROS2003_Workshop/hayward/,
http://www.ep.liu.se/ecp/010/007/ecp01007.pdf.

Some other research works are more oriented to shape generation. The applications can be classified as follows:

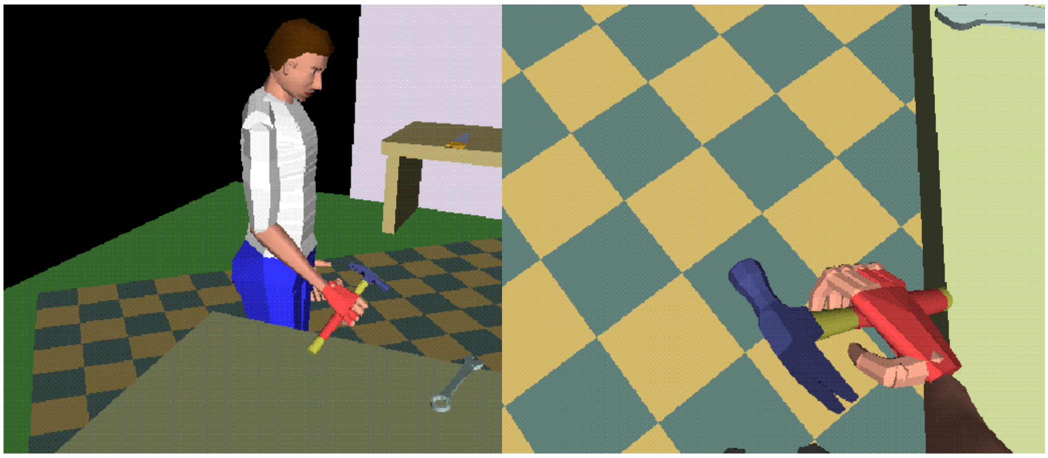
Touch added to existing CAD applications
This mostly regards commercial CAD packages where a haptic device is connected in a way similar, or alternative to, an input device (pen, tablet, etc.). That doesn't really add new paradigms for interacting with the model, the haptic device is optional as the CAD program must be fully functional even in case it is not present, via a standard keyboard/mouse set. It just offers a better interaction with the model in case the haptic device is present.

CAD applications specifically written for Touch
These are mostly experimental applications written with the purpose of fully taking advantage of the potentialities of a haptic device. These applications usually offer new paradigms for model interaction, supposedly intuitive, 3D, with force feedback, allowing non conventional manipulation of the model. In this case the haptic device is not optional and the application is not functional without it.

There are a number of cases where the designed objects are made of non-rigid materials; however, the haptic rendering of non-rigid objects is still not a mature technology as its very high computational requirements make it difficult to be implemented on nowadays machines, so research in this field is very active. There is a very high demand for this kind of technology also in the medical field (body parts are mostly non-rigid); this is not strictly related to engineering and manufacturing, but it is worth a mention.

Hereafter there are some few examples of *CAD applications specifically written for touch*; they are haptic feedback shape modeling systems, based on different methaphores: "Virtual 3D painting", "Virtual sculpting" and "Virtual milling".

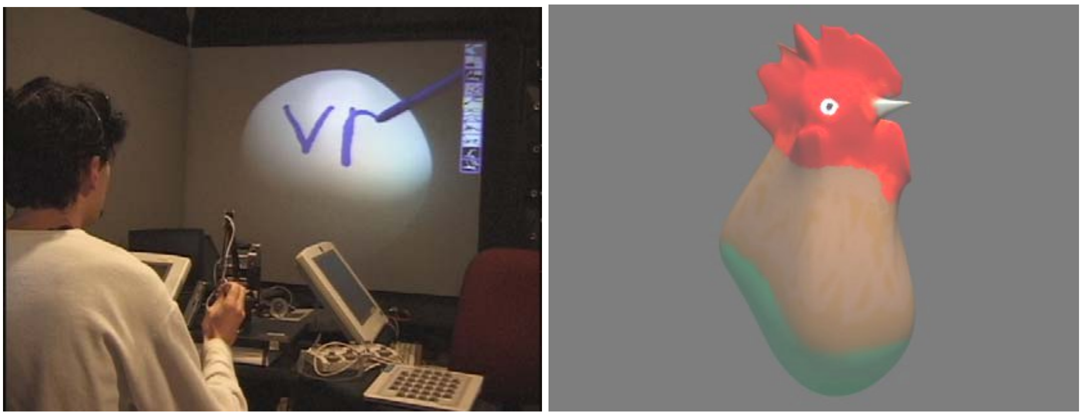
Dextrous Haptic Interface for Jack
This is an integration between Jack, a full-body simulation software, and the Rutgers Master II, a hand sensing and force-feedback device. The concept of a Virtual Human Agent is also proposed as a mean for the user to interact with the virtual scene.



(reference:
Popescu V.G. and C. Burdea G.C.
Dextrous Haptic Interface for Jack
http://www.caip.rutgers.edu/vrlab/publications/papers/1998_asme.pdf)

inTouch

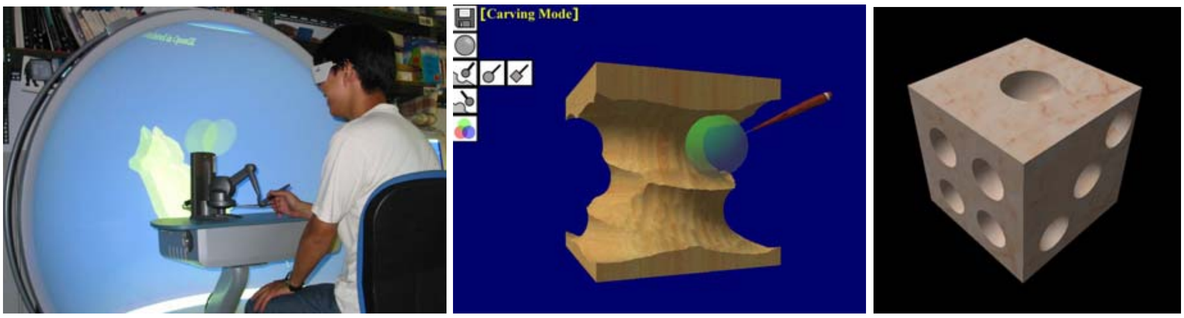
inTouch is a system aimed at "3D painting", which is actually a shape modeling system for creating polygonal meshes and colouring them, in an interactive, intuitive way. Haptic feedback is given through Sensable's PHANToM device.



(reference:
Gregory A.D., Ehmann, S.A., Lin M.C.
inTouch: Interactive Multiresolution Modeling and 3D Painting with a Haptic Interface.
http://www.cs.unc.edu/~geom/inTouch/GregoryEhmannLinVR00.pdf
http://www.cs.unc.edu/~geom/inTouch/)

Virtual Sculptor

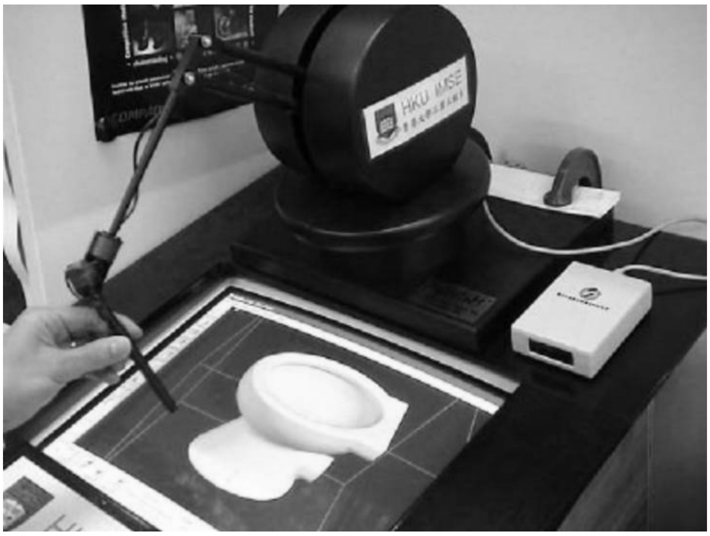
The Virtual Sculptor is a shape modeling system based on the sculpting metaphore. It makes use of stereo viewing, a spherical display, a PHANToM device and an Extended Marching Cube (EMC) algorithm for preserving sharp features.



(reference:
Lu Y, Wang W., Liang R., Ouhyoung M.
Virtual Sculptor: A Feature Preserving Haptic Modeling System
http://www.cmlab.csie.ntu.edu.tw/publication/pdf/ITP0207.pdf)

Haptic Rendering of Milling

The following research regards a haptic-based shape modeling system where the object is created by a virtual machining process. The user acts like he was driving the machining through a telemanipulation system; though, the machining is simulated. The reaction forces are computed through a mathematical model integrated with coefficients determined via a real telemanipulation-driven milling machine, stored in a look-up table. The haptic device used is the PHANToM by Sensable Technologies.



(reference:
Zhengyi Y. and Yonghua C.
Haptic Rendering of Milling.
http://www.mle.ie/~ian/EuroHapticsNet/2003/03.pdf)

The only commercial system for shape modelling available today is *Freeform* by *SensAble technologies* [http://www.sensable.com], a CAS system based on a haptic exploitation of a voxel representations, already mentioned in § 3.3.2. The system provides classical shape generation tools, based on extrusion or rotation of profiles in order to "save time" by allowing the user to define an initial block closer to the final expected shape. This process is understandable but up to some extent it is a sign that spherical tools are not sufficient.

The analysis of state of the art shows that none of the applications mentioned above provides satisfactory solutions for shape generation and modification, as envisaged in T'nD project. Therefore, further research on haptic systems, shape modeling and their integration is required.

6. Conclusions

This report has presented the state of the art in the three main research fields of the project: haptic technology, advanced shape modelling technology, and cognitive ergonomics. The state of the art has been investigated taking into account the objectives of the project.

For what concerns hardware technology, it results from the analysis of state of the art of haptic devices that an extended version of FCS HapticMaster is the most appropriate hardware solution for the project. The FCS HapticMaster can be used as basic platform, equipped with a strong and stiff 6-DOF device carrying simulated clay modelling tool with two handles.

For what concerns software technology, the analysis of academic and commercial modeling applications has pointed out the need for the project of further investigating and developing sweep-based and voxel-based techniques. The major open issue that has to be addressed concern the definition of an appropriate theory allowing discrete schemes to support fine quality shape generation.

The report also includes an overview of ongoing activities aiming at integrating haptic systems with modelling environments, with particular reference to shape generation. None of the ongoing works found in literature addresses and provides solutions for shape modeling and modification issues as required in the T’nD project. Issues related to real-time re-computation of the shape model modified through the use of the haptic system require to be investigated.

Finally, in the area of cognitive ergonomics it has been identified the necessity to extend usual ergonomics criteria and principles with new aspects that will be developed analyzing T’nD designers’ cognitive processes. The new principles will then be adapted to the specifications of T’nD haptic and shape modelling systems.