Sound And Tangible Interfaces for Novel product design

STATE OF THE ART UPDATE

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Abstract
This document presents the results of work package WP1 State of the art update where the more recent achievements in the scientific and technological domains addressed by the SATIN project are described. In particular, the domains addressed are the following: haptic technology, sound technology, visualization technology, shape modelling technology, and Human Computer Interaction.

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0. Index

1. Extended Summary

This report presents the analysis of the state of the art in the various domains that are of interest of the SATIN project. Most of these research domains have been addressed, even if separately, by some research projects where the SATIN partners have been involved in. Examples of these research projects are FP5 FIORES and SMARTSketches, and FP6 T'nD. Besides, some domains have been addressed by projects such as FP5 TouchHapsys, FP6 ENACTIVE and HAPTEX. Most of the state of the art reports of the above mentioned projects are public. Therefore, this report aims at providing an updated version of the already existing reports, and referring other documents and papers where appropriate. This avoids repetitions on one side, and allows anyway those SATIN partners who are not knowledgeable in a specific domain to retrieve all information and references necessary to gain appropriate knowledge in order to participate and contribute to the project technical discussions and decisions. The sections of this document have been mostly written by the academic, research and developer partners. The domains addressed are: haptic technology, shape modelling technology, sound and visualizations technology, and human computer interaction.

In haptic technologies it is concluded that SATIN required the whole hand type device and that the only feasible solution is that of a local surface patch. Issues related to this include moving bases, adaptive surface patch or 'slice', feeling of sliding, material and number of degrees of freedom and encountered or full contact – sensors on or above the strip.

In the shape modelling sections the technologies which will be considered for their suitability within the SATIN project are advanced global deformation operator and collision detection techniques for real time.

The sound technology section concludes that for real time synthesis for a real and intuitive sound requires the development of faster algorithms.

With regard to visualization technologies there are various display options including HMDs, projection based technologies, holographics, responsive and reactive workbenches. Discussions concerning which is the most suitable method will be made in the next stage of the project.

Human and computer interaction section considers research that applies to tangible and sound interfaces specifically related to SATIN. This includes the characteristics of tangible and sound interfaces and the application of multimodal interfaces to product design. Interactive system requirements are discussed and the practical considerations in technology design, Human Factors issues and equality and diversity which need to be addressed throughout the project.

These final recommendations will feed into the next stage of the project.

2. Introduction

This report is the first in the first deliverable D1.1 if WP1 of state of the art update for the SATIN project (IST-5-034525)
The aim of deliverable is:

- To provide an initial update of state of the art in technology and related research.
- To add to existing body of work from published literature and relevant other European activities.
- To provide an integrated overview of scientific and technical progress

Two versions of this deliverable will be produced – version 1 will provide an initial summary of knowledge at the beginning of the project, and then version 2 will address the same key areas but focus specifically on the needs and requirements of SATIN.

The structure of this report focuses on the key aspects of the SATIN project and draws upon expertise within the consortium.

The key areas of focus are the following:

- Haptics technology: advances and innovations in area of the most recently developed haptic interfaces (PoliMI, FCS)
- Shape modelling: advances in sketching, shape modelling (PoliMI, think3. INESC)
- Sound technology: advances in auditory displays, sound technologies (TUE)
- Visualization technologies (INESC)
- Human computer interaction: integration of sensory control modalities (visual, auditory, haptic) in multimodal interfaces, human computer interaction and interactive systems design (UNott)
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Appendices are available for haptic technology data sheets (appendix A) and: a summary overview of available stereoscopic HMDs (appendix B).

This deliverable reviews these areas and provides final conclusions specifically to SATIN.

3. Haptic technology

This section presents and update of the state of the art in the domain of haptic technology. Several reports have been published in the context of some research projects and are publicly available. Therefore, the aim of this section is proposing an update of what already published, which is duly referenced hereafter. The section starts proposing taxonomy of haptic technology for the classification of available technology and devices according to various dimensions. The following section provides examples of technologies belonging to the taxonomy.

3.1. A taxonomy of current haptic technologies

Current haptic technology is a varied field. Devices range from the very small to the very large and from the very simple to the very complex. This section will provide an original, systematic taxonomy of all currently known types of haptics devices. This will be particularly relevant to the SATIN project, since SATIN can only attain its goals by an optimal combination of several types of devices which are so far usually seen as distinct, almost mutually exclusive modalities.

Every large overview of a new field faces the problem of organizing the material in a logical and coherent way. In a very new and inherently unorganized field, a chronological, historical overview may be the logical choice. Such an overview will show the winding paths that previous workers have taken, reviewing the devices produced so far, without passing a final judgment on the most suitable type of technology as yet. The excellent overview [1] produced by the ENACTIVE Network of Excellence is a prime example of this strategy. A more systematic approach may be taken, if the purpose of the overview is limited to a clear subset of the devices. The T'nD project produced a ranking of the devices in its applicable subset of devices, along dimensions of performance metrics [2].

For *SATIN*, the search space is much wider than in T'nD, because it now encompasses both force and shape displays. Still, a systematic approach is even more desirable in this case, since we need to home in on the proper combination of haptic technologies needed for this ambitious project. Hayward [3] orders his own recent work on scales of size and level of rendering detail. We will follow this idea, but applied much more rigorously, to the whole field of haptics known today.

Possible dimensions in the taxonomy

The common denominator of all haptic devices is that they all seek to make an impression on the tactile or kinesthetic senses of the user. These senses act on different size scales, the smallest scale being perceived within the skin (tactile sense), and the larger scales mostly in tendons, joints and muscles (kinesthetic senses, usually called haptic in the more limited sense of the word).

A closely linked issue is the relationship between the total physical workspace of the device, and the part of that workspace that is being displayed simultaneously at any given point in time. This is related to the necessary number of degrees of freedom (DOF's) of the device, which we will discuss in some detail later.

The level of detail in the haptic world could be termed as the "spatial frequency content" of the haptic experience. Another important frequency is the temporal one. Devices will vary in their frequency response, i.e. the speed with which they can react to external forces, or display virtual forces to the user. This quality is closely linked to the range of haptic experiences that a single device can stably provide, ranging from the sensation of free air, to that of a high stiffness surface. The range of impedances that a device can render is sometimes called the "Z-width" of the device.

Other important issues are the absolute size of the workspace, maximum forces, as well as the co-location in time and space (co-registration) of the haptic modality with other modalities, typically graphical and auditory.

Lastly, there is a number of implementation issues including the type of control and the type of drive used, the kinematics and whether they are grounded to the world or to the user, and the question whether the device is of the full contact type, or of the encountered type.

We will discuss the various dimensions of this taxonomy in some more detail in this section, and then give an overview of the haptic field ordered along these dimensions, in the next section.

Size scales

Human users can haptically perceive the world around them on scales ranging from the reach of the human arm (order of 1 meter), through that of the spreading and grasping fingers of the hand, (order of 0.1 meter), via details felt by the skin of the finger tips and palm of the hand (order of 0.01 to 0.001 meter, i.e. down to 1 millimeter), all the way down to surface roughness or texture which may live at the micrometer level, and which can only be explored by sliding the fingers over a surface. The first scale is perceived by movements of the arm, with receptors in joints, tendons and muscles. It is usually referred to as the kinesthetic or haptic scale. The second scale is felt by exploring and grasping movement of the fingers, perceived through a combination of kinesthetic clues and the skin deformation indicating the orientation of the surface touched by the fingers. It is usually referred to as tactile/haptic. The third scale is explored by various receptors in the skin, and referred to as tactile. The fourth scale is perceived by high-frequency receptors in the skin, and is often referred to as vibrotactile. A complete haptic interface would be able to display all of these scales.

Degrees of freedom (DOF's)

The number of degrees of freedom indicates the level of detail that the device can render simultaneously at any given time.

point-based force feedback interfaces

Classical haptic devices are point-based, i.e. they give force feedback in a single point. A general force has components in the three directions XYZ, so these devices are 3-DOF. They typically have three motors (or brakes, in the case of passive devices).

The natural extension is to render torques in the same point of interest. This leads to 6-DOF devices, usually joystick-like interfaces which exhibit torques as well as forces.

The six degrees of freedom can also be used to render forces in two closely spaced points, which the user can grasp with two fingers. The torque around the connecting line between the two devices is traded for control over the distance between the two fingers, so pinching and grasping forces can be rendered. Such devices do not exist as a product, but they can be built by combining two 3-DOF devices, although this usually leads to workspace conflicts.

tilting (and curving) surfaces

Some experimental devices add local degrees of freedom to the end-effector of point-based force feedback devices. These may take the shape of small plates tilting under the finger, or thimbles tilting on a movable roller. Sometimes these effects take the place of "normal" degrees of freedom, substituting a haptic illusion for true 3-D motion (Morpheotron).

shape and contour interfaces

Shape interfaces exist at various scales, from the larger contour devices, to tactile "pincushion" type devices. They are usually based on some form of grid. The number of degrees of freedom often equals the number of grid points, but in some cases each grid point can do more than just rise vertically, and the number of DOF's may be even larger. In any case, the number of DOF's of shape interfaces is usually much larger than in point-based force feedback interfaces, but the workspace of each individual actuator is usually much smaller.

Grounding and kinematics

Haptics devices can be either fixed to the inertial world ("grounded"), or "worn" by the user, i.e. attached to the user's shoulder, arm or finger ("exoskeleton" or "wearable"). Examples will be shown and discussed in the next section.

A mechanical division which is sometimes relevant is that between "serial" and "parallel" mechanisms, depending on whether the actuators all follow each other link by link, as in classical robotic arm, or whether they all link directly to the end-effector, as in a classical six-leg flight simulator motion platform. Hybrid forms do exist, and a well known 3-DOF parallel robot is the Force Dimension "Delta" robot (see *Appendix A* for details).

Mechanical redundancy is sometimes used to increase the rotational workspace, or to avoid difficult poses known as "singularities" or "gimbal lock". Redundancy means that more actuators are used than the final number of DOF's at the end-effector would strictly require. A special form of redundant, parallel mechanisms is formed by the "wire" robots like the Spidar [33]. Here, the legs are replaced by cables. One or two extra cables are always needed to keep the other cables pretensioned.

Drive type

Haptic devices can be active, passive or hybrid. *Active devices* have some form of drive capable of adding energy to the device. This drive can be electrical, hydraulic, pneumatic, etc. We will leave out some exotic devices based on magnetic levitation or other technologies which from first principles will never be able to reach the levels of force of workspace relevant to the SATIN project.
Passive devices employ some form of braking, e.g. electro-mechanical, or electro-rheological.
Hybrid devices use braking for large forces and stiffness, and power for the more subtle effects.
A special case is formed by nonholonomic devices, which use the sideways blocking action of actively orienting wheels, to define surfaces passively. The name "cobots" has been coined for such robots, to emphasize their safety in the presence of human users. Since the non-side slipping wheels act in a way similar to brakes, cobots form a special family of the hybrid devices.

Control type

Force feedback devices come in two types: impedance controlled and admittance controlled. The majority of devices are impedance controlled. *Impedance controlled* devices are mechanically designed to "render" free air, i.e. low mass and low friction when passive, and to render virtual walls by energizing the motor to give to the user a resisting force. Their causality paradigm is: the user inputs displacement into the device and the device responds with force. *Admittance controllers* are the dual. They carry a force sensor at the interface to the user, and their causality paradigm is: the user inputs force to the device, and the device responds with a displacement. Admittance controlled devices are usually built much stiffer and more robust, since their internal displacement controller loop can cancel their own friction, and to a large extent also their own inertia.

Contact type
A major dichotomy in haptics devices is whether the user is in continuous contact with the device even if the user is not touching anything in the virtual world, or whether the device is only contacted when something is "touched" in the virtual world. The latter type is called the "encountered" type of device. Most force feedback devices are of the first type and most shape and tactile devices are of the latter type; but there are exceptions to this rule.

The classical VR application of a control stick or a steering wheel in a flight simulator is technically an encountered device, although the user stays in full contact with it during most of the simulation. The force feedback part of the device is more like a classical full contact device, but the shape of the stick and the first contact with the surface is definitely encountered. Similar considerations apply to medical simulators for minimally invasive surgery, which typically use scissors handles as an interface to the user.

More general encountered devices come in two distinct varieties. There are those devices which try to copy the whole virtual object, which remains stationary in the workspace. These devices need a great level of detail, but do not need to adapt very fast.

Then there are devices which copy the shape of a small part of the virtual object. The device needs to adapt its shape quickly, but does not need the full number of DOF's to render the whole object. Pin-cushion type tactile devices typically fall into this category, but larger shape displays also qualify. The shape of the part of the virtual object which is momentarily rendered depends on the position of the user's hand in the workspace. A limiting case is where the shape display is very simple, perhaps just a flat surface oriented in the same direction as the surface of the virtual object.

Taxonomy dimensions are summarized in the following table.

Taxonomy dimensions	Description
SIZE SCALES	Human perception of the world according to scaling factors.
DOF	Level of detail that the device can render simultaneously at any given time.
GROUNDING AND KINEMATICS	Haptic device is fixed to the inertial world or it is worn by the user.
DRIVE TYPE	Active device, passive device, hybrid device.
CONTROL TYPE	Impedance controlled devices. Admittance controlled devices.
CONTACT TYPE	Continuous contact of the user with the device. "Encountered" type of device.

3.1.1. Hierarchical taxonomy of existing devices

The previous section has examined the various dimensions that span the space of all known haptic devices. We will now select an ordering of these dimensions that best suits the purpose of the SATIN project.

SATIN aims at building a relatively detailed haptic display with a large workspace, and a medium level of simultaneous detail in the area felt by the human hand. We will therefore order current devices along a continuum ranging from large workspace, low detail devices at the one end, down to small workspace, high detail devices at the other end. This will give us a basis to select a suitable combination of these devices by systematically selecting devices from the applicable levels in this continuum. The table below gives an overview of the hierarchical taxonomy selected. The next section will give examples of each of these technologies.

HIERARCHICAL TAXONOMY OF EXISTING DEVICES	
3-DOF and 6-DOF haptic robots	(workspace : human arm)
opposing	
serial	
impedance control	
admittance control	
parallel	
stiff links	
cable links	
exoskeleton	
grounded	
wearable	
passive and hybrid drive robots	
cobots (nonholonomic)	
Grasping displays	(workspace and number of DOF's: human fingers)
5-DOF	
gloves	
Surface display	(workspace and number of DOF's : human hand surface)
locally approximating surface	
full contact (force feedback)	
encountered (tracking position display)	
full shape display	
full shape display	
grid type	
mesh type	
fixed object copy	
Tactile display	(workspace and number of DOF's: single finger skin)
pincushion devices	
Vibrotactile display	(workspace and simulated scale:microscale)
vibrotactile display	
sliding surface	

3.2. Examples of current haptic technologies

This section applies the taxonomy developed in the previous section, to currently existing devices.

3.2.1. Existing force feedback displays

1-DOF and 2-DOF displays

There is a number of mostly experimental designs of haptic machines for a very limited number of degrees of freedom. For a complete overview, refer to [1] and [2]. In general haptics, and certainly in the SATIN project, these devices are only relevant as design exercises for devices with three or more degrees of freedom. Due to their limited applicability to the domain, we will not list them here extensively.

3-DOF and 6-DOF displays

The largest workspaces of all haptic devices are typically spanned by classical point based force feedback devices. These devices typically have a low number of degrees of freedom, ranging from 3 (point-based force feedback interfaces), to 6 (including torques). The level of spatial detail which these devices can render may be quite high, but this detail is not rendered simultaneously. This is why we consider these devices to be on the one extreme end of our taxonomical continuum. They have the largest workspace, and the lowest level of simultaneous detail of all haptic devices considered.

Several overviews of this type of devices are available. Two good ones come from previous EU funded work, viz. [1] from the ENACTIVE Network of Excellence and [2] from the Touch and Design project.

The first types discussed are the most common, 3-DOF and 6-DOF impedance controlled devices.

Opposing type

We will first list those machines which are typically standing on the ground or on a table "opposite" the user, instead of "alongside" the user as in the next category of exoskeletons or "wearable" devices.

Most 3-DOF and 6-DOF haptic robots are of the impedance controlled type with serial kinematics.

- serial kinematics

- impedance control

The classic example of this first category of "opposing type" serial robots is Sensable's Phantom. Commercial products include the following, listed alphabetically. Specifications of the most important of these machines are reported in *Appendix A*.

CEIT large workspace gantry robot

DLR Lightweight Robot

Haption Virtuose 3D and 6D

Immersion CyberForce

Cubic 3 (former MPB Freedom 6S)

Sensable Phantom 3D, 6D

- admittance control

A special subset of the (serial) haptic robots is those using an admittance control strategy. Only one commercial device is available in this class, and it is this one which will be used as a basis in the SATIN project, viz. the FCS HapticMaster. The only other high quality device in this category was the Excalibur, a laboratory prototype. The other examples are industrial robots, modified to carry encountered shape displays.

Excalibur

Excalibur [4] is a laboratory prototype of a control stick mounted on an XYZ table, much like a printer/plotter. It was built as a one-off, and subsequent copies were not made despite requests by Boeing. A price tag of $ 1M was quoted for a copy of this relatively simple machine.

FCS HapticMaster

The FCS HapticMaster [5] is the only admittance-controlled haptic device on the market. The appendix gives the specs of the machine. The FCS HapticMaster will be used as a basis for the development of the SATIN haptic device.

Yokokohji WYSIWYF

Yokokohji [6] tested a Puma robot fitted with a force sensor under the name WYSIWYF ("What you see is what you feel"). Yokokohji claims that the term "admittance control" was coined by McNeely from Boeing, who was also among the first to suggest the encountered type of haptic devices. Clover and McNeely claim that Yokokohji [7] coined it.

Yoshikawa

Yoshikawa [8] was among the first to report on a device which in retrospect should be called "admittance controlled". His early work was on a one-dimensional grasper. His later work centers on encountered devices.

- parallel kinematics

Parallel haptic robots are less common than the serial type. They have certain advantages, in particular their higher mechanical stiffness-to-weight ratio. A major disadvantage is the more limited workspace, especially in the rotational degrees of freedom. Commercial and scientific examples of the stiff link variety include:

- stiff link parallel robots

Except for the Pantograph device, these type of devices are basically hexapods.

Force Dimension Delta, Omega (and Novint Falcon)

The Force Dimension Delta and Omega devices are very nice commercial implementations of a 3-DOF parallel robot architecture called the "Delta robot". See the specs in the *Appendix A*.

Iwata "Haptic Master"

Iwata is a prolific designer of conceptually interesting haptic devices [9]. The "Haptic Master" is an example of a multi-link parallel device.

Univ. of British Columbia / Quanser Pantograph 3D, 5D

McGill University is a center of research on parallel robots. Hayward [10] has suggested the use of the two-arm Pantograph principle in haptics, and this has been extended by Qanser into a 5-DOF commercial device, see the appendix. The drive is of the usual capstan-cum-quadrant type.

Univ. of Colorado pen based haptic interface (5-DOF).

The University of Colorado built a 5-DOF device somewhat similar to the Qanser device, but with a different drive principle. This is based on pushrods running between friction wheels [11].

- cable type parallel robots

Cable type parallel robots are all of the same, fully parallel, redundant type. They include:

SPIDAR G

Sato [12] created one of the best known examples of the parallel cable-type device.

WireMan, VIDET

The University of Bologna has used the wire cable paradigm to create passively braked point-based wearable displays for the blind [13].

Exoskeleton or humanoid type

- grounded

The serial, grounded "exoskeleton" or humanoid robots at first sight do not distinguish themselves very clearly from the serial, grounded "opposing" type discussed before. However, we will distinguish them here on the basis of their typical "cooperating" type of setup. This type of exoskeleton or humanoid arm is typically grounded near the user's shoulder, and the kinematics and number of degrees of freedom closely follows that of the human arm and, in some cases, the human hand. The number of actuator degrees of freedom is typically larger than in a serial device of the "opposing" type, and sometimes redundancy is present in the number of actuators, relative to the number of degrees of freedom of the final end effector.

Argonne arm (UNC-CH)

The Argonne arm is an early example of a large workspace, whole hand interface which partly follows the geometry of the human arm.

Barrett WAM

The Barret WAM (Whole Arm Manipulator) is a somewhat humanoid arm with one degree of redundancy. It is controlled by an impedance algorithm which implicitly solves for the redundancy.

PERCRO Arm Exoskeleton

The PERCRO grounded exoskeleton and hand is one of the highest quality haptic research devices found to date. Virtual objects can be touched more or less convincingly, but exploring the surface, and especially with more than one finger, is still unsatisfactory.

Sarcos Dexterous arm

The Sarcos Dexterous Arm [14] is a development of the early Argonne type of arm. See the Appendix A for an impression of the device.

Southern Methodist master Arm (pneumatic)

The Southern Methodist University has an exoskeleton that is worth mentioning, because it is pneumatically driven. See http://engr.smu.edu/me/syslab/PHI/MasterArm.html.

Vishard

The Vishard is an experimental, multiply-redundant articulated arm [15]. When switched off, it hangs limp like a human arm. When switched on, it takes on a shape where most joints are in a default position of approximately right angles. Drive is through harmonic drive gearboxes. The control is of a hybrid impedance / admittance type. The arm is very flexible, and the virtual mass and/or friction presented are quite high.

- wearable

Wearable exoskeletons usually are of the hand or finger type. Reaction forces are set off on the lower arm or shoulder of the user, so high forces cannot be rendered realistically.

Some of the less spectacular wearable haptic arm types will be mentioned further down under combination devices. Active wearable devices are almost always of the hand-interface type, and we will discuss them under the grasping interfaces.

Passive and hybrid drive robots

A special class of robots which we have not considered above is the passive types. These devices typically display forces by braking, using either electrical brakes or magneto-rheological fluid brakes. "Hybrid" devices use a combination of brakes for large, passive forces, and small motors for small, active forces.

These robots come in all shapes and sizes, but most often in the class of wearable devices. Brakes are lighter and have lower power requirements than their motorized counterparts.

Passive devices have been largely left out of the above overview of robotic haptic displays, because they are by their nature very limited in the type of geometry they can render.

Cobots - nonholonomic robots

Nonholonomic robots are a special variety of (partly) passive robots. They use orientable constraints (usually steering rollers) to block movement completely in certain directions, and allow it fully in others. These robots can display certain simple constraints, but like the other passive devices they are very limited in the range of shapes and stiffness that they can render, and are hence not suited to the purposes of the SATIN project. "Cobots" is a name coined for some of these devices, to indicate their intrinsic safety when working "with" humans. North Western University in Evanston (Chicago) is the center of activity for this specialized type of haptic robot.

3.2.2. Existing grasping displays

Grasping displays are typically the next step down from point-based interfaces in terms of workspace, and the next step up in (extra) number of degrees of freedom. The workspace is typically that of the human hand, and the number of degrees of freedom is that of the number of fingers. There are two common types of grasping display: one strategy is to use two or more point-based interfaces to render forces to index finger and thumb; the other strategy is to add brakes or motors to the bending of each individual finger. These devices are typically wearable, and the reaction forces are typically set off on the wrist or lower arm of the wearer.

point-based haptic displays with grasping

This group contains experiments in using several point-based haptic interfaces to present forces separately to the index finger and the thumb.

Melder / Harwin

Harwin [16] has created a setup for two and three fingers by using a Phantom desktop haptic display for each finger involved, carrying a thimble. The workspace is very limited due to kinematical conflicts between the separate devices, but the sense of grasping and lifting a virtual object is very adequately represented by this setup

PERCRO Pure Form hand exoskeleton

The Pure Form project uses a combination of wearable and grounded haptic devices to present force feedback to two separate fingers in a large workspace. The "wearable" two finger exoskeleton can be mounted on to the grounded "Exos" arm exoskeleton, to create a grounded 5-DOF haptic display for two fingers.

Univ. Washington 2-DOF finger haptics display

force feedback gloves and exoskeletons (wearable)

Force feedback gloves have a long history, preceded by unpowered "data gloves" which are only used for tracking hand gestures.

CyberGrasp.

The Cybergrasp device is a powered glove where the fingers are driven by Bowden cables (push-pull cable in a sheath). It can be worn on the lower arm, although a lot of flexible cabling to ground restricts the movements of the user. It can also be combined with the Cyberforce haptic arm. The overall impression of both devices is very bad. Neither strong nor precise forces can be rendered, and the impression of touching a virtual object is never reached. Only some random jerky motions are perceived when approaching a virtual object.

Rutgers Master force feedback glove

The Rutgers force feedback glove is a wearable design. Reaction forces between the fingers and the palm of the hand are created by small plunger type actuators. There are several versions of this device, with up to 19 degrees of freedom in four fingers and the thumb.

Wisconsin Haptic Gripper.

Springer et al. [17] built a multiple-finger exoskeleton with a separate arm at the upper side of each finger, carrying a thimble supporting the fingertip from a sort of pendulum.

3.2.3. Existing surface displays

Local surface displays

We will use the term "local surface", or "locally approximating surface" display for those devices which present to the user a local, oriented surface, instead of just a single point of contact. This surface may then be either mounted on a full-contact force feedback display, or alternatively positioned at the point of interest by a position controlled robot. The surface may be either flat, or it may be selectable from a limited number of optional sides of an interface block, each carrying a specific generic shape like a ridge or a valley.

free local object

The simplest way of representing a local object is by just putting a simple shape on the table, and allowing the user to manipulate it while looking at a "different", virtual object. It has been argued that this gives surprisingly convincing results (this is reported in [18]).

However, this will only be satisfactory in the context of a user manipulating one or more small objects, and this is not of great relevance to the SATIN project.

local surface on a full contact force feedback display

There is a class of very interesting devices where the impression of touching a point on a virtual object is enhanced by a local surface patch into the sensation of touching a recognizable patch of the surface with one or more fingers. There are a few experimental setups examining the usefulness of this concept.

Stanford contact location display

Provancher et al. [19] are doing interesting research on a Phantom device fitted with finger contact thimbles which contact the haptic device via a contact roller, instead of via the usual swiveling gimbal. The roller is moved under the thimble, giving the finger the impression that the surface under the thimble has a certain orientation. The impression of sliding or rolling the finger over a curved surface can be created in one direction only. The roller is driven by an actuator strapped to the user's arm, via a push-pull rod connecting to the thimble on the finger.

McGill Morpheotron

Hayward et al. [20] at McGill University have shown that by tilting a finger platform surface, an illusion of gentle curvature and depth can be created even in flat plane motion. The "Morpheotron" device is just a passive psychophysical proof-of-concept device, consisting of a free running carriage on a table, with a tilting surface attached to the wheels by a crank. It is not a practical virtual reality device at all, but it has shown that tilt does contribute to the perception of shape, and that programmed tilt can actually simulate gentle curvature of motion even in straight line motion. It is an example of the potential usefulness, although limited in this case, of haptic illusions.

Robles de la Torre

Another haptic illusion explored by Hayward and Robles de la Torre [21] does not even require a tilting surface at all. It is the illusion where a "bump" is felt during sideways motion, when sideways forces are induced. This illusion works on a smaller size scale than the "Morpheotron" illusion, and is also not strong enough to completely eliminate the need for vertical motion in devices displaying anything else than gently undulating, but basically flat surfaces.

Touch and Design project

The European Touch and Design project (http:// www.kaemart.it/touch-and-design) has created a prototype of a local surface interface which goes a step beyond an oriented local flat surface. It displays not just the orientation, but also the local curvature (in two dimensions) of the surface patch. This idea, in an elaborated form, is likely to be used in the SATIN project.

local surface on an *encountered* display, with tracking

Local surface displays can also be of the encountered type. This is a more or less obvious idea, in the first place since the local surface is an approximation of the often stationary object and in the second place because it is difficult for a local surface display to follow the user's hand or finger in full contact, without giving spurious force or orientation clues in free air.

The problem with the local surface display as an encountered display is that the local surface must follow the user's hand around, in order to be at the right place at the right time for the user to touch. This requires some form of free air tracking of the user's hand, which is a difficult problem in itself.

Johns Hopkins "VisHap"

The "Vishap" system [22] uses a Phantom as the platform for a very small object of a shape appropriate to part of the virtual world to be rendered, e.g. a push button. The user's hand is tracked by a camera vision system, and the device is slaved to the user's hand. When contact is made, the force feedback is applied in the usual, penalty based, impedance controlled manner.

Tachi - fixed shape block on a position tracking robot

Tachi [23] describes a prototype of a 6-DOF impedance controlled device, carrying a fixed shape block with various ridges and corners. This block is kept close to the user's hand, with the appropriate side of the block tracking the expected point of contact. In this ways, a ridge or a valley can be presented to the user at the proper point in space. The user's fingertip is attached to a separate passive linkage for tracking the finger tip position, so the encountered robot can move to the proper position. Later versions of the device seem to revert to a flat encountered surface, and the tracker is now partly worn as an exoskeleton, even though it is grounded behind the back of the user.

Yokokohji "WYSIWIF" display

Yokokohji coined the phrase "What You See Is What You Feel" [7], for an encountered device based on a PUMA robot driven in position / admittance control, carrying a fixed shape like a tennis ball or a round handles. The user can "meet" this round shape in space, and after grasping it, manipulate it.

Yoshikawa

Yokokohji et. al. [24] have created an encountered-type device where a position controlled robot follows the human hand, keeping a ring floating around the hand. The ring carries a number of finger pads, which stop at the right moment to display forces to each individual finger.

Full shape displays - encountered

We will call a "full shape display" a device which presents to the user the shape of an object touched by the human hand. These displays are almost invariably of the static, encountered type.

square grid type

Most of the full shape devices built so far has been of the "square grid" type. These are basically 2.5 D devices in the sense that they consist of a rectangular grid of large pins, which can come up vertically out of the grid surface, much like a very large version of the usual "pin cushion" tactile devices. These devices are severely limited in the types of shape they can represent. Some examples follow.

Iwata "Haptic Screen" - "FEELEX"

An early attempt at a shape display is Iwata's "Haptic Screen". It is a 20 * 20 cm deformable rubber skin, driven by five ball screw actuators. Since then, this has been developed into FEELEX 1 and FEELEX 2 [9]. These are 6*6 arrays of vertical pins under a rubber screen. The smaller version has a resolution of 8 [mm] and can simulate tumors under human skin.

Pisa haptic box, MR free hand shape interface

Bicchi et al. [25] have developed a very basic 4 * 4 grid type shape display based on varying the damping in large MR fluid cells. The shape is very difficult to judge, and the surface is very flexible.

Poupyrev "Lumen"

"Lumen" is a project by Sony. It consists of a grid of pushbuttons with lights in them. The drive is by SMA (shape memory alloy), hence the stroke, force and speed are far too weak for serious haptic interaction.

Tachi "PopUp" SMA coils

Tachi [23] built a grid type shape display based on coils of SMA (Shape Memory Alloy). The resulting display has centimeter resolution, and a considerable vertical stroke, in the tens of centimeters. However, resolution and speed of operation are limited.

curving mesh type

More recently, interesting attempts have been made to create surfaces which are more like an actively curving mesh, supported or grounded at only a few positions and free to take on more complex shapes of double curvature.

Georgia Tech "Digital Clay".

"Digital Clay" is a heroic attempt to create a desktop-sized, fully controllable mesh surface using massive numbers of ultra-miniature fluidic actuators. Very interesting theoretical work has been done so far, but a working prototype remains to be made.

Noma ground surface simulator

Noma et al. [26] have built a ground surface simulator which is based on a triangular mesh. However, the resolution is not fine enough as a haptic simulator for the human hand.

Joysnake

Not really a haptic device at the moment because it is not force sensitive, the "Joysnake" serpentine robot interface [27] is still interesting from a mechanical point of view. It is a remote control interface to a crawling robot in the shape of a snake, actuated in two DOF's at every joint. The Joysnake can be considered as a single line version of the curving mesh type of interface.

predefined real world objects

A very effective type of shape display which is easy to overlook, is the use of the actual object. This way of representing a virtual object is very common in practical applications. The most obvious example is in the use of copies of the actual handle, steering wheel or knob in haptic display of aircraft cockpits in flight simulators, and similar trainers for cars and ships. An example of a haptic knob has been developed by Politecnico di Milano [28].

A generalization would be the use of exchangeable objects (drinking cups, doorknobs etc.), e.g. on haptic devices for training patients in daily life activities during rehabilitation after stroke.

The option feels like cheating, but it is very effective in cases where the user interacts with the virtual world through tool handles and the like. It is also the option selected in the Touch and Design project for reproducing the feel of a clay scraping tool. However, it is less suitable for the exploratory interface needed in the SATIN project.

proximity sensing
Encountered devices typically need some form of tracking of the human hand, in order to reposition and reshape the device in expectance of the user's imminent touch. Sensor types for following the user's hand in free air include contacting types like passive links with angular position sensors like potmeters or encoders, or non-contacting types which are often based on visual or magnetic tracking.

3.2.4. Existing tactile displays

Tactile displays are invariably of the rectangular grid type. The most common is the "pin cushion" type of vertical pins with small (millimeter) vertical displacement. Electrical, pneumatic suction and vibrating stimulation also occur. Hayward's sideways moving "comb" type pins are a recent innovation.

Harvard tactile display using RC servomotors

The Harvard display [29] is one in a long list of pincushion displays with a large block of identical motors under the display to push and pull tiny pins in the grid under the fingertip.

ITACTI / SmartTec piezo-ER display

The European ITACTI consortium (http://www.itacti.com) created a Braille-like flat tablet display. It is being marketed by SmartTec in the UK.

SmartFinger

This is a voice coil actuator from Tokyo University, worn on the nail of the finger, which adds tactile cues to the finger without touching the skin.

SmartTouch

This is an electro-coutaneous skin stimulator from Tokyo University, substituting electrical impulses to the tactile nerves for physical pins.

STReSS (Hayward, McGill)

The STReSS device is of the pin-cushion type, but with sideways displacement of skin. The device is an interesting variation on the normal pin cushion type of display. The underlying idea is that skin sensations can be aroused by stretching the skin sideways, instead of pushing it in and out. A comb-like set of piezo strips is pulled sideways to generate tactile sensations. The principle is promising, but prototypes still leave something to be desired.

The idea that tactile sensation is generated purely by shear deformation of the skin, not by any actual depth cues, is supported by psychophysical experiments where the skin is locally sucked in by a small air orifice in a flat surface. The resulting sensation is that of a pin prick. Apparently the skin has no way of knowing whether it is being stretched by an inward or an outward local "bulge", and the physical; default expectation is that it is being pushed in by an object from outside.

3.2.5. Existing vibro-tactile and friction displays

The sensation of "incipient slip" is important to grasping and lifting (virtual) objects. We tend to pick up things by pinching just hard enough to prevent them from slipping through our fingers. The phenomenon of slipping is sometimes referred to as "tactile flow" in the psychophysical literature, and some research has been performed on barber-pole type illusions that can occur in the same way as in optical flow [25].

No really feasible device has yet been developed to display the tactile flow sensation. Two ways seem open. Either the sensation is represented by vibratory inputs to the skin of the fingers with a "conventional" tactile display, or the actual slip condition is physically applied. The latter could be done conceivably by a miniaturised treadmill device. Full size treadmills are sometimes fitted onto moving base platforms to form a combination device for "displaying" an undulating road for subjects to walk on. Similarly, a "miniature belt sander" could be mounted upside down on a haptic device to display the slipping surface, or to keep the display surface stationary in inertial space while the haptic base moves under it. Changing the direction of slip movement quickly would remain an unsolved problem with a belt type device. The Johns Hopkins University did some experiments with an inverted trackball.

Exeter vibratory tactile display

Summers [30] created a vibratory tactile display capable of rendering vibrations in the range from 25 [Hz] up to 400 [Hz]. It uses a 10 * 10 array of points, individually driven by piezo-electric actuators. The device has been used to do psychophysical research into skin simulations using patterns of vibration. No explicit effort into simulating the (incipient) slip condition was reported.

Johns Hopkins slip display

The Johns Hopkins tactile haptic slip display [31] is a motor driven trackball. The user's finger rests on the ball, and experiences slip when the ball rotates. The device has been mounted onto a Phantom haptic device, and has been used for some basic psychophysical research on JND's (Just Noticeable Differences) in tactile slip perception. The reference also points to a publication by Chen and Marcus on an earlier "belt sander" type of 1-DOF slip display.

3.2.6. Existing combination displays

The SATIN project will need a combination of the virtues of some of the devices mentioned earlier in this chapter. This section examines some combinations that have been used by others, in an attempt to add more haptic detail to devices with a fairly large workspace.

cascaded multipoint interfaces

A number of examples has been reported of using the combination of two different types of devices viz. a haptic arm and a force feedback glove, or a fingertip display, to display contact forces to two or more individual fingers. Examples are the Immersion Cybertouch - Cybergrasp and the PERCRO Exos.

This type of device only rates as a combination device here, because their components can be used separately as a point-based force feedback device and a force feedback grasping interface. These devices present a number of force points to the user, instead of just one. The number of powered DOF's is typically limited to that of a point-based interface, with one extra DOF for every finger powered separately.

The CyberTouch and CyberGrasp devices have been discussed earlier in this chapter. Immersion offers the two devices as a combination. The very flexible "grounded exoskeleton" type haptic robot carries a slow, cable-driven force feedback glove. Only one of these setups has been sold, since the quality is absolutely insufficient. When touching virtual objects, only a jerky impression of the presence of the object a virtual object is felt.

parallel multipoint interfaces

There have been several cases where identical devices have been used to display forces to thimbles on individual fingertips, and some of these have been mentioned under the grasping interfaces. Examples are the use of two and three Phantoms by [16], and the GRAB interface, where two identical devices for the index finger and the thumb of one hand come from left and right. In a sense, all powered gloves, including the PERCRO Exos device are of this type.

cascaded (local) shape interfaces

The "local surface displays" described earlier [19] are all examples of combination devices, since the tilting surface is useless if not mounted on a point based haptic display. Especially the Touch and Design setup points the way that could be used in SATIN.

cascaded haptic plus (vibro-)tactile interfaces

Some of the devices that can represent the sense of almost slipping have also been used in combination with point based haptic displays. This is true for the Johns Hopkins tactile slip display which was mounted on a Phantom, and also for the device reported by [32], a piezo tactile display mounted on a passive, wearable arm with magneto-rheological brakes.

3.3. Proposed haptic technologies for further examination within the SATIN project

3.3.1. Conclusion on the state of the art in large-scale haptic shape displays

When we survey the field of existing haptic devices, we come to the following conclusions: no satisfactory demonstration of the sense of touching and exploring the shape of an object using point-based devices with powered gloves and/or tactile interfaces has been reported to date.

Exploration of simple, generic predefined objects in virtual space has been demonstrated by Tachi [23], but the usefulness is very limited. In fact, exploration of an arbitrary virtual surface by hand has never been demonstrated by any haptic device. Preliminary results using haptic illusions have been obtained for very low curvature surfaces, in Hayward [20].

The European Touch and Design project has shown an early prototype of a shape display for surfaces with local order of curvature up to G2, i.e. with single degree of curvature in two arbitrary principal directions. The area is very new indeed.

3.3.2. Review of the suitability of available display principles for SATIN

The purpose in the SATIN project is to create a haptic device, and software, for rendering a moderate number of degrees of freedom, in a large workspace, to the whole hand. The surface to render will be smooth, so there is no need to display details below a scale of a few centimetres.

Tactile technology is not applicable. The scale of the surface curvature is much larger than that of the human fingertip, and a hand-sized tactile interface is completely unfeasible.

Grasping interfaces with one or more finger contact points are also not applicable. It is not likely that a limited number of point contacts will provide an acceptable perception of shape exploration. These devices are more suitable for manipulation of fairly small, moveable virtual objects.

A set of predefined shape blocks is not a feasible solution either, because the surfaces to render in SATIN have a variety of curvatures, both positive, negative and of the saddle plane type.

Grid type shape displays do not seem like an optimal candidate, because these have a tendency to "display" the edges of the square rising bars, unless a very stiff flexible surface would be applied on top of the bars, as a mechanical "anti-aliasing" low-pass filter on the spatial "frequency" of the grid bars or "pixels". Also, the number of grid points needed to display the variety of curvatures over the surface would be quite large, and could not be reduced in areas that are locally flat.

The mesh types of shape display would seem to come closer to the requirements. This type of display has a more natural inclination to be smooth and continuous than the grid type devices. Straight areas would need only very small displacements of the local actuators. However, no feasible short term implementation of this type of device has been implemented so far. Also, as in the grid type of device, the number of actuators needed to create the variety of curvatures is the product of the smallest curvature to be displayed anywhere in the scene rendered simultaneously, with the size of that full workspace.

The only feasible technology that efficiently utilizes the fact that the surface to be displayed in SATIN is of relatively low order, albeit in a large workspace, would seem to be the local surface type of display.

3.3.3. Proposed technology to examine for SATIN

It is proposed to examine in SATIN those solutions which make efficient use of the fact that the surfaces to be displayed in SATIN are smooth and fair, and do not create the need for displaying very sharp surface detail.

This type of display would have to be of the "whole hand" type. Due to the number of degrees of freedom involved, the only feasible solution is that of a local surface patch. This will have to assume the local curvature of the surfaces to be rendered in real time.

moving base

The workspace requirement means that the basis of this local device must be either a wearable exoskeleton, or a grounded device with a large workspace. It is expected that the local surface display will have considerable complexity, hence mass, so a wearable device does not seem like a good idea. Most impedance controlled grounded devices are quite incapable of supporting any serious amount of machinery, or eliminate its apparent mass. Following this reasoning, the use of an admittance controlled device like the FCS Haptic Master seems a good choice.

A 6-DOF platform based on two FCS Haptic Masters has been created in the Touch and Design project. However, the control of the two machines has remained in the two separate control threads in the two separate control computers. For optimal results, this will have to be upgraded to a solution with a single control computer, controlling the hardware (sensors and actuators) of both machines, from a central 6-DOF dynamical model.

adaptive surface patch or "slice"

The size of the local surface patch will have to allow the user to explore the surface in stroking movements. There is a trade-off to be made between the size of the patch and its complexity on the one hand, and the speed with which the base can move the patch, to follow the hand of the user, on the other hand.

It is proposed to make the surface fairly large in the direction of the expected hand movements, i.e. in the sideways direction as viewed from the user. This is also the direction in which more curvature detail is expected on the virtual objects. In particular, the surface can be implemented as a curving ribbon, displaying a "slice" or cross-section of the car, or other object touched.

feeling of sliding

Exploring movements to left and right on the surface of this "slice" will display to the hand of the user the actual momentary shape of the surface, over a fairly large range of motion. The user's hand will slide over the strip surface in this direction. If the strip is not as long as the width of the full workspace, the base will have to move in order to follow the human hand, to increase the effective workspace.

Experience will have to tell whether the human hand will feel that it is being "cheated" with regard to the speed at which the surface slides under it. Early psychophysical research [31] indicates that the JND's (Just Noticeable Differences) in this respect are not critical at all, so there is good reason to expect that if the shape of the strip can be made to adapt in the proper way, the resulting impression of sliding over a stationary surface will be very realistic.

Exploring in the direction nominally away from the user will have to be done entirely by motions of the haptic base, as in a point-based exploring motion. The "ribbon" will move away form the user, with the hand of the user resting on it and feeling its shape modulating as it runs across the virtual object. No impression of sliding will be created, unless some form of vibrotactiile or "belt sander" display is added in this direction at right angles to the strip.

material and number of degrees o freedom

The number of degrees of freedom (DOF's) of the strip will depend on the variability of the surface to be rendered, and on the length of the strip.

Moreover, if the strip is not as long as the full width of the workspace, it will have to move while the virtual object is stationary. The strip will then have to adapt its shape while the base is moving, to stay "the same" in inertial space. This puts serious requirements on the ability of the strip to take on arbitrary shapes, and the speed and smoothness with which the shape can be modified. It becomes mandatory that the strip can take on the same shape everywhere along its length, and that the contours which it can render can "travel" along its length like a wave of constant shape.

These requirements would point to a fixed number of equally spaced actuators, deforming a fairly stiff strip (a physical spline) which can conform to curves of exactly the same order as the number of actuators present, not more and not less. The spline will enforce a physical representation of a polynomial, e.g. cubic spline. More detailed requirements will have to be found, and a design made for the spline and the actuators.

encountered or full contact - sensors on or above the strip

If the user remains in full contact with the strip at all times, the base can follow the user's hand by conventional force feedback. However, it is to be expected that the apparent mass of the device will be such that considerable contact force is needed to generate enough surface friction for the fingers of the user to "drag" the device in this way. This is inconsistent with the desire to allow the hand to explore the surface freely, at least in the direction along the length of the strip.

A design study needs to be made on the possibility of slaving the position of the strip to that of the human hand, without exerting the force needed to accelerate the virtual mass of the base device. It may be possible to achieve position sensing of the human hand with moderate, continuous pressure contact, using strip position systems like Infusion System's SlideLong.

It may be preferable to find a completely force free, non-contacting way of tracking the user's hand, or an intermediate solution.

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4. Shape modelling technology

This section presents an update of the state of the art in the domain of shape modelling. Different approaches are presented, especially the promising sub-division technique that still requires investment to become industrially usable. Both aspects of the modelling generation and the modification are considered. Finally, a short description of what should be investigated for SATIN project concludes the section.

4.1. Examples of current shape modelling technologies

4.1.1. Technologies for modelling class A surfaces

As a general definition, we are calling class A surfaces the ones that have the best surface quality and aesthetic properties. These surfaces are required for the visible parts of products, since they convey all design intents in direction to customers. In the car industry they are defining exterior car bodies, as well as interior, like dashboard. For consumer products they are also defining the shape of the product. These kinds of surfaces are obviously the targeted ones for the SATIN project.

Technologies for modelling class A surfaces need to generate and to maintain aesthetic properties and fairness. While applied to industrial product, this has to be combined with arbitrary topology as well as with accurate constructions constraints.

Such aesthetic properties require at least curvature continuity. Various interrogation methods have been developed to detect surface irregularities and to assess the fairness of these class A surfaces. Isophotes, reflection lines, and highlight lines are the first-order interrogation methods that are used in the automotive industry to assess the fairness of a surface [1].

A novel paper extended recently the concept of highlight/reflection lines to circular highlight/reflection lines [2] by replacing a family of parallel light lines to concentric light circles. This method is claimed to provide an observation of the surface fairness in all directions but considering the observation parameters we state that this method has also some drawbacks as the standard ones. As a matter of fact, any function of a surface normal vector is susceptible to constitute a first order interrogation method.

In current commercial CAD products, traditional techniques still involve explicit surfaces based on tensor-product, Bezier or NURBS representations [3]. Hence class A requirements, in addition of the visual flow of reflection lines are also checked upon curvature continuities among adjacent trimmed surfaces within defined tolerances (depending of various companies), and checked upon control points distribution.

Nevertheless, while this is true for the final product model, the continuities requirements are higher than simply curvature G2 geometric continuities during the modelling phase. For instance G4 continuity is needed for creating a G2 blending of surfaces.

In addition of very well known standard tools already presented in the State of the Art of Tn'D project [3], at our knowledge, the only novelty in class A modelling is coming from freeDesign and think3.

The new company freeDesign [4] is providing shape modelling based mainly on filling regions defined by curves manipulated interactively. They do not publish on their site the technology they are using, but since this is from Alynn RockWood we think it could be the same as the "Multisided patch technology" he did for the Curventa Inc. modeler (2001). By the way this could be related to this published paper [5].

The other novelty is coming from think3 who introduced recently the new Target Driven Design (TDD) approach [6].

In the traditional approach, with the currently available tools, a designer with specific intent can only apply a very long trial and error process in order to get his intent. The designer mainly access the shape by manipulating indirect controls, and so can check only afterwards the results to be in accordance to his intent.

TDD approach gives to the user access to targets as request of a shape generation or modification. These targets can not only be positional constraint, but can include a wide range of aesthetic intent features, including silhouettes or highlights.

This is also a result of previous CEC projects FIORES I & II [7], where 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.
Regarding TDD modifications, they are quite independent of the mathematic representations and they don't require a particular topology.
Global Shape Modelling (GSM) [6] (see section 4.1.3) implements TDD modifications, and recent advances of GSM enable designers to target directly on a section curves, a highlight curve or a silhouette curve and GSM will automatically compute the desired modification on the entire model whatever the underlying topologies or surfaces mathematic representations.
FIORES-II results [7] are also implemented in think3 software, as curves modifiers i.e. aesthetic intent features.
Regarding TDD generation, as results of CEC project T'nD, sweep techniques under constraints combined with ongoing developments will allow to directly generating a shape having a highlight distribution as close as possible to a specified one.
Regarding both aspects TDD generation and modification, Target Curvature Plot is the newest feature of advanced think3's TDD approach. Designers can use this function to tune the shape of a set of continuous curves by editing its curvature plot. Without this tool, designers might spend hours tuning the curve(s) to reach a desired curvature plot. With this new feature the designer can design a curvature plot and impose it to selected curve(s) in seconds.
Finally mixing interactive definition of complex target curves and TDD generations and modifications are also very interesting modelling technologies. The following chapter about sketch based modelling is dedicated in certain manner to this point, but may be not all focused on class A modelling. Nevertheless think3 software already provides class A tools to sketch curves on tablets as Free Hand curves that can be then used as complex target for silhouettes, highlights, sections.

4.1.2. Technologies for modelling subdivision surfaces

Introduction
In the field of computer-aided design (CAD) and related industries, the de-facto standard for shape modelling is at present Non-Uniform Rational B-Splines (NURBS); NURBS representation, however, uses a rigid rectangular grid of control points and has limitations in manipulating shapes of general topology.
Subdivision surfaces provide a promising complimentary solution to NURBS: they were first described by Catmull and Clark in 1978 [8]. Just after NURBS were identified as being a sensible standard for parametric surface descriptions, for twenty years subdivision surfaces were considered as an interesting generalisation of NURBS.
Subdivision surfaces are a very attractive alternative to classical patches for free form geometric modelling because of their flexibility and robustness: one of the main advantages and distinguishing features of subdivision is its ability to model arbitrary topology smooth surfaces and special geometrical features, with complex constraints at corners. In contrast, classical NURBS methods require careful patch layout and cross boundary continuity management to build complex shapes: in practice this often leads to the appearance of not desired kinks and cracks, especially when complex patches are animated.
A lot of interest has recently been shown in subdivision surface schemes and their interactive rendering: the basic idea of subdivision is to define a smooth surface as the limit surface of a subdivision process in which an initial control mesh is repeatedly refined with newly inserted vertices. The subdivision rules, according to Catmull and Doo & Sabin [8, 9], produce surfaces that can be proven to converge to a piecewise B-spline where the original vertices are the control points.
On the practical side, many recent algorithmic developments have moved applications of subdivision surfaces rapidly forward. Examples include, interactive multi-resolution editing [10], reconstruction of sampled data with subdivision surfaces [11], direct evaluation at arbitrary parameter values [12], inclusion of boundary conditions and smoothness constraints [13], trimming

[14], approximation with subdivision surfaces [15], simulation of the mechanics of surfaces [16] for engineering design [17], non-manifold subdivision [18], and many more. In fact, techniques are mature enough for deployment in movie production [19] and many geometric modelling packages (e.g., Mirai, Maya, 3DMax, etc.). Subdivision surfaces are now one of the methods of choice in Computer Graphics, and some consider that they might succeed NURBS as the standard in engineering CAD.

Overview of subdivision

A subdivision scheme is defined by a set of topological rules and geometric rules for mesh refinement:

- The topological rules define how the connectivity of the control mesh is split into a refined mesh;
- The geometric rules are used to compute the exact coordinates of the refined control vertices.

In literature, one may find rich families of subdivision approaches in constructing various subdivision schemes and in optimizing existing subdivision schemes for better surface behaviour.

These schemes can be grouped according to a number of basic criteria indicating whether they are:

- Approximating or interpolating, with respect to the original control mesh point positions: examples of approximate subdivision schemes include Loop subdivision [20], Doo–Sabin [9] and Catmull–Clark [8] subdivision, while interpolator Butterfly subdivision [21], Kobbelt subdivision [22], and interpolator √2 [23] and √3 subdivision [24, 25] are interpolating schemes.
- Stationary or non-stationary subdivision: if the subdivision rules change or not during the subdivision process; most of the existing subdivision schemes are stationary subdivision schemes.
- Based on quadrilateral, triangle, or hexagon faces as basic primitive.
- Primal or dual type depending on the split rule: the topologic step of a primal scheme is described as a face split while dual schemes employ vertex splits.
- Uniform or non-uniform subdivision: according to the existing mesh is refined uniformly through mid-point knot insertion over the entire surface for all levels of subdivision. Most of the existing subdivision schemes are uniform subdivision schemes. The NURBS subdivision scheme [26] can, however, perform parameterized and non-uniform subdivision.
- Global or local or adaptive subdivision: if the rules are designed to perform global subdivision; in certain situations, a local and adaptive subdivision might be desirable [27].

When designing geometric rules for mesh subdivision, key properties need to be considered. They include affine invariance, finite support with small subdivision masks, symmetry, and behaviour of the limit surface. Techniques for series analysis (such as Eigen structure analysis, z-transformation and Fourier transformation) are often used to guide the selection of appropriate subdivision masks. In literature, one may also find combined schemes that incorporate one or more of the topological rules [28, 29, 30]. Loop subdivision surfaces are generalizations of three-directional box-splines [31]; while most of the reported schemes are further generalizations of a subset of splines [32, 33, 34], some other subdivision schemes are further extensions of box-splines [35].

Many of the existing subdivision schemes can handle sharp features, such as crease and boundary edges [36, 37]; sharp features can be classified according to the number of vertices meeting at a vertex and the type of a vertex or an edge.

The last few years have seen rapid development of fairly comprehensive theory and algorithms for basic surface subdivision, reaching a certain level of maturity, however, in practice Catmull-Clark and Loop subdivision are the most frequently deployed methods [34].

During the past years groups of new subdivision schemes were proposed, many new theoretical tools were developed, and various practical results were obtained: in fact subdivision algorithms, if implemented properly, can form the basis for a wide range of extremely fast and robust interrogations. There is space for further development dealing with:

- Unified subdivision schemes and standardization: an important step towards wide practical applications is the pursuit of unified subdivision schemes; such a unified generalization should cover all what we can do with NURBS, including the exact definition of regular shapes such as sphere, cylinder, cone, and various general conical shapes and rotational geometry.
- Continuity conditions at extraordinary corner positions: another topic is the lifting of continuity conditions at extraordinary corner positions in handling general degrees that should be the same as that for regular part of subdivision surfaces.
- Manipulation tools: For wide practical use, advanced manipulation tools, such as trimming, intersection, offsetting, Boolean operations, visual effects must be developed. While there have been various attempts [14], there is significant space for further development in these areas.
- Other important topics include further development in surface fitting [15] and interpolation, faring subdivision surface generation, subdivision surface modelling from curve nets, mass property evaluation, geometry compression, interfacing issues and compatibility with existing parametric surface software, adaptive subdivision algorithms that lead to the same limit surface.

4.1.3. Local and global surface deformation techniques

The State of the Art of Tn'D project [38] is already providing references for such local and global surface deformation techniques. In particular Gibson and Mirtich wrote a good survey [39] presenting some purely geometric approaches for modelling deformable objects, and focused on physically based models.
The authors would also like to mention the work done in a former company, while in the CEC FIORES project [40].
Very recent update of such state of art can be found in [41], as tutorial notes of Eurographics 2006 in the “Shape deformation” chapter. There are several new papers related to the subject, but it is worth to mention they are not focused on class A modelling, but rather oriented to animations (attracted by entertainment/game industry) and surfaces reconstructions, so mainly oriented to deal with mesh evolutions or large scattered data points.
In [41], **Surface-based freeform deformations** are discussed, and recent paper [42] could improve this technique. Then **Space Free Form Deformations** (FFD) allow deforming any shape topology in a smooth manner since all shapes are embedded in a 3D space deformation. This other recent paper [43] uses radial basis function where a fair function is found by minimizing energy functional. Improved details handling can be provided by **Multi-resolution Hierarchies** which can enhance any freeform deformation technique, by applying deformation only to low frequency components, high frequencies being first separated (by mesh smoothing), and then applied back to the deformed surface (by displacement vector / volume [44]). While multi-resolution or multi-scale hierarchies are an effective tool for enhancing freeform deformations by fine-scale detail preservation, the hierarchy generation can become quite involved for geometrically or topologically complex models. To avoid the explicit multi-scale decomposition, **Deformations Based on Differential Coordinates**, another class of methods modifies differential properties of the surface instead of its spatial coordinates, and then reconstructs a deformed surface having the desired differential coordinates, recent advances being in [45, 46].
Skeletal mesh extraction could also be in this category, [47] is using Voronoi-based skeletal mesh extraction from a given original mesh, dedicated to animations.
Another advance in modelling deformation is presented in [48]. This new approach integrates parametric and implicit partial differential equations (PDE) to define geometric solid models containing both geometric information and intensity distribution subject to flexible boundary conditions.

Advanced Global Shape modelling deformation operator (think3)
Already mentioned in the above chapter on Technologies for modelling class A surfaces, the GSM tool of think3 [49] was first introduced in late 2000. This is a global deformation tool such that any kind of modelling objects (points, curves, surfaces or solids with arbitrary topologies) can be deformed in a same smooth and accurate way. This is achieved under precise high order constraints (currently up to G2), that can be declared as preserving conditions (continuity with the

parts that are not changing) and/or as target conditions (to be satisfied after modification). The topology of such constraints is arbitrary, that makes the tool very flexible. The set of usable constraints is rather rich, since it is possible to combine points, curves and surface boundaries constraints, as well as planarity, symmetry, or projections constraints. In addition target sections, silhouettes and highlights are also available.
This tool is rather well adapted for class A deformation.

4.1.4. Sketch-based modelling and surface editing

Illustrations and sketches are the starting point of any design process to create innovative manufactured products. However, most of existing modelling interface continue to explore the WIMP (Windows, Icon, Mouse and Pointing) approach instead of taking advantage of new pen-based devices which are more adapted to users with sketching skills. During the 90's, research on calligraphic interfaces attempted to overcome this limitation by proposing sketch-based modelling systems such as the SKETCH [51] and Teddy [52]. SKETCH combines drawing and gesture recognition on a 2D interface by using constructive operators targeted at solid modelling. This work allows sketching on a 3D view by using a predefined gesture syntax which was adopted by more recent approaches [53, 54]. Alternatively, Teddy was the first free-form system based on contour strokes to model 3D polygonal surfaces. This work proposed natural sketch based-operators to construct bend, cut and smooth surfaces. However it was only able to model one simple polygonal object at a time. Over more recent years, sketch-based modelling has brought more flexible interfaces which adopt implicit surfaces to overcome Teddy's limitations [55, 56] or use advanced mesh representations [57] to offer more flexible free-form operators. However these mathematical models are still not mature and are too restrictive to be used in industrial applications. An alternative research focus on extending free-form operators [58] to NURBS models at the cost of less naturalness interactions. On the other hand [59], proposes a 2D interface for creating B-Spline surfaces using constraints to add more precision to sketching. However, this work only supports simple extrusions or revolution surfaces as compared to the more natural editing operators mentioned above.
Most of the reviewed work uses TabletPCs or similar small-scale interfaces. However, the emergence of affordable large scale displays brings new approaches and applications to bear on modelling tasks. Following the sketch based approach; the first attempts were limited to create curves and surfaces following traditional modelling techniques from the automotive industry [60]. For example, during the last four years, several research works proposed virtual taping as the essential modelling paradigm over large scale displays using different tangible interfaces [61, 62, 63, 64]. This popular concept was also extended to virtual environment based on head mounted displays (HMD) devices which allow representing more complex 3D curves [65, 66]. On the other hand, new tangible interfaces and hardware devices were presented to interact using the workbench metaphor instead of large scale displays [67, 68], or taking advantage of HMD to support collaborative modelling scenarios [69]. However, none of these approaches present a solution for both 3D constructive modelling and surfacing flexible enough to model complex objects such as car bodies or buildings. Furthermore, these do not really take advantage of large screen displays, restricting their interaction to near screen operators such as the taping technique. Finally, multimodal interaction is still under-used and limited to speech commands as a complement without providing a flexible framework to support synergistic input modalities to perform modelling tasks, which constitutes the main focus of our proposed research.

4.1.5. Commercial products

We already presented some related industrial tools from think3, in particular GSM [49], which is up to now and at our knowledge, an unsurpassed commercial product in term of so called “class A” shape deformations. Here after a list of think3 competitors we aware of:

- Autodesk Alias, www.autodesk.com/alias: Looks like FFD, probably using subdivision surface, no internal continuity preserved, as far as we know.
- ICEM, www.icem.com. Global deformation available, no real constraints.

- Dassault, http://www.3ds.com. Global deformation available, no real constraints. A new tool is usable only with Subdivision surfaces, not targeted to class A.
- Rhino, www.rhino3d.com. They announced the availability of their tool, supposed to be based on the work of [70]. We are seeking to check the validity of resulting shape.
- PTC, www.ptc.com, they have a limited FFD, the resulting shape quality is disputable.
- UGS, www.ugs.com, no real global deformation? UGS is talking about Requirements-Driven Design, which could sounds like think3 Target Driven Design. Actually these are engineering mechanical constraints to be applied, and a link to a PDM system. They are not dealing with complex class A surfaces.
- FreeForm, www.sensable.com, still cannot be for class A. This was analyzed in [71] and [72].

4.2. Future developments in shape modelling technologies

Target Driven Design (TDD) will be developed further, understanding more semantic from the user for target specifications. Obtaining the target from a haptic, gesture or sketch input will be part of these developments. In this aspect SATIN project is on the path of these future developments in shape modelling technologies, since the target for a new shape will be directly given by the user as a haptic input.
Sub-division techniques constitute a very promising approach that, as mentioned above, still require investment to be industrially used. In particular their coexistence with legacy data and operations related to all downstream treatments (i.e. after the first shape generation) must be well undertaken. However we conjecture that combined with TDD approach it might become the next generation tool for shape modelling waiting a simpler but more complex to theorise approach based on discrete geometry.

4.3. Proposed shape modelling technologies for further examination within the SATIN project

4.3.1. Advanced global shape deformation operator

The GSM deformation technique is what we envision to use as starting point for this project. It will be in the frame of WP3 theoretical foundations to deeper specify in which conditions this technique will effectively be apply to SATIN.

4.3.2. Collision detection techniques for real time

Collision detection is an important component of many applications in computer graphics. In particular, it is a critical question for virtual environments applications, where real time performance is required to provide the feeling of being immerse in a environment that looks and is interactive like a real one.
There are many implementations of collision detection schemes. Paper [73] relates collision detection techniques according to its 3D model representation: constructive solid geometry, implicit and parametric surfaces or polygonal models. Much of the work done in collision detection for virtual environment applications is supported by polygonal models. To find collisions, polygonal models are organized in hierarchical bounding volume (BV) structures to improve the performance of the collision detection process. The classic scheme for hierarchical collision detection is a simultaneous recursive traversal of two bounding volume trees *A* and *B*.
There are four major toolkits to solve the narrow phase of the collision detection, based on bounding volume hierarchies that determine intersecting triangles between two objects. They differ on the type of bounding volume implemented. SOLID [74] and TurboCD [75] use axis-aligned bounding boxes (AABB). RAPID [76] implements oriented bounding boxes (OBB); and QuickCD [77] uses *k*-dops.
It is very difficult to compare different approaches since performance also depends on the shapes of the models, type of contact, size of the models and others [73, 77].

The main advantage of collision detection toolkits based on AABB is that AABB are faster to intersect. When using AABB, only six comparisons are required to find out if two axis-aligned bounding boxes overlap. It is also possible to say that two AABB are disjoint, in the best case situation, with only one comparison. Another advantage of using AABB is that it is simple to update these volumes as an object rotates and translates. The SOLID library performs better than previous toolkits based on AABB but still yields worse performance than OBB trees for rigid models. The TurboCD toolkit [75] is faster than RAPID, identifies intersecting surfaces and uses parallel techniques to improve performance.

RAPID approximates 3D objects with hierarchies of oriented bounding boxes (OBB). An OBB is a rectangular bounding box with an arbitrary orientation so that it encloses the underlying geometry more tightly. The representation of an oriented bounding box encodes position, widths and orientation. The main advantage of RAPID is that OBB are better approximations to triangles reducing effectively the number of intersecting operations with better performance than other toolkits.

The QuickCD toolkit builds a hierarchy tree of “discrete orientation poly-topes”. Discrete orientation polytopes, or “k”-dops, is convex bounding volumes whose faces are determined by half-spaces whose outward normal vectors come from a small fixed set of “k” orientations. The main advantage of QuickCD is that “k”-dops are better approximations to the underlying geometry than AABB with the advantage of its low cost compared to OBB. QuickCD best results were comparable with RAPID. However, a major drawback of QuickCD is that allows only one moving object.

Since collision detection is a very demanding task, researchers are also working in using existing graphics accelerated boards (GPU) [78, 79, 80, 81, 82, 83] or dedicated hardware [84, 85] to accelerate collision detection by hardware.

Algorithms using graphics hardware use depth and stencil buffer techniques to determine collisions between convex [78] and non-convex [79] objects. CULLIDE [80] is also a GPU based algorithm that uses image-space occlusion queries and OBB in a hybrid approach to determine intersections between general models with thousands of polygons. Further improvements of CULLIDE are FAR [81], which considers reliability, and Quick-CULLIDE [82] that studies self-collisions. MRC [83] deals with large models composed of dozens of millions of polygons by using the representation of a clustered hierarchy of progressive meshes (CHPM) as a LOD hierarchy for a conservative error bound collision and as a BVH for a GPU-based collision culling algorithm.

These GPU-based algorithms are applicable to both rigid and deformable models since all the computations are made in the image-space. Collision detection methods using GPU have the disadvantage that they compete with the rendering process, slowing down the overall frame rate. Furthermore, some of these approaches are pure image based reducing their accuracy due to the discrete geometry representation.

Collision detection with dedicated hardware acceleration techniques

for “k”-dops bounding volumes has been experimented [84, 85]. An ASIC [84] and a FPGA [85] collision detection single-chip was developed with two main stages, one for traversing simultaneously a hierarchy of “k”-dops and one for intersecting triangles. The ASIC and the FPGA implementations are up to 1000 and four times, respectively, faster than the software intersection tests on a standard CPU.

4.4. References

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5. Sound technology

The research takes place in the tradition of the ecological psychology (Gibson, 1966) of hearing. The most important theoretical points of departure are summarized in the next two principles. First, in identifying and categorizing perceived objects humans will use, if available, information from various senses and, within one sense, they will use multiple sources of information. Second, the information they use is preferable information that enters the perceptual system distributed over a large sensory array. For instance, in determining the material of an object, e.g., a ball, they use vision, hearing, touch, temperature, and their kinesthetic senses. A wooden ball has another colour than a metal ball; when the balls collide the sound of a wooden ball differs from that of a metal ball; a wooden ball will in general feel rough, while a metal ball feels smooth; a metal ball feels colder than a wooden ball, and a metal ball is heavier than a wooden ball.

These properties of the perceptual system make it a very robust sensory system. If sensory information from one sensory modality is lacking or inaccessible, we can use the information from another modality; if part of the sensory array is obscured, we can derive what we want to know from information entering through another part of the sensory array. We conclude that in every day perception the perceiver uses coherent sources of information in order to identify and categorize perceived objects. This gives us the theoretical explanation why adding sound and haptics to visual virtual environments, when properly times and designed, will make these environment more natural and intuitive, and in this way facilitate tasks to be carried out in these environments; see, e.g., Díaz et al. (2006) which also gives an overview of current literature in this respect, for instance as to the issue when multimodal presentation of stimuli will increase or decrease performance. A systematic and technical account of the problem field encountered in using sound in robotics and virtual reality is presented by Pai (2005).

5.1. Examples of current sound technologies

Four locations will shortly be discussed where research has been carried out on the use of synthetic sounds in virtual environments. In the European project "the Sounding Object" a number of synthetic sounds have been designed for use in animations and virtual reality situations. A number of demonstrations can be viewed and listened to at: http://www.soundobject.org. Most of the synthesis algorithms are based on simple physical models of the objects involved, and include pouring water, rolling wheels, foot steps, etc.

At the University of British Columbia in Vancouver, fast algorithms have been developed for the synthesis of impact sounds produced by colliding solid objects or, e.g., spherical objects rolling in plates. The models consist mainly of physical simulations of the acoustics of solid virtual objects (e.g., Doel et al. 1998; 2001). This has resulted in realistic synthetic sounds produced by, e.g., a ball rolling in a metal plate or bowl. The objects, in general, consisted of rather stiff, solid objects, while the impacts were short. As a result, friction does not play an important role in the sound generation process. The sounds produced by more viscous objects are not modelled. Furthermore, no complex haptic interactions were included in these simulations.

The know-how at Vancouver has been transferred to Rutgers University in New Jersey, USA, predominantly in the person of Dinesh Pai. A really multisensorial laboratory has been built there for virtual reality studies covering three sensory modalities in a coherent way, i.e., the Haptic, Auditory, and Visual Environment (HAVEN). The HAVEN is a multisensory virtual environment, optically and acoustically isolated from the rest of the world. The space is acoustically damped by preventing parallel surfaces and covering the walls with absorbing panels. Sound can be presented through a number of speaker boxes. Haptic devices can present haptic feedback. Moreover, the HAVEN is densely packed with sensors. The positions, the motions, the postures, and the exerted forces can be monitored and used interactively in communicating with the participants in the HAVEN. Information about the research carried out there can be found at: http://www.cs.rutgers.edu/~dpai/mcl/currentResearch.html.

Finally, at the University of Eindhoven, besides some explorative studies on the synthesis of sounds produced by water, wind, and solid objects, extensive acoustic and perceptual studies has been carried out on bouncing and rolling sounds (Houben et al. 2004; 2005; Stoelinga et al., 2003; Stoelinga, 2007). The results of these studies and those of others (e.g., Grassi, 2005) can directly be used in the sound synthesis algorithms for the SATIN project. The most important aspect that up to now escaped the satisfactory synthesis of really realistic sounds is presumably that friction is not included in the physical models on which the synthesis algorithms are based. One of the main challenges of the SATIN project will be to find out how friction can be included in the synthesis algorithms in order to simulate to sounds produced by the more viscous materials used for the shaping of artefacts.

5.2. Future developments in sound technologies

Sound technology, as far as it is relevant for application in virtual reality environments, will develop in various directions. The real-time synthesis of realistic and intuitive, interactive sound will require faster and faster algorithms. The more interacting objects and acoustic interactions will be presented in the virtual environment, the faster the algorithms must be in order to synthesize the sounds in real time.

The physical phenomenon that up to now escaped realistic physical modelling is friction. This has limited the application of the synthesis algorithms to stiff solid objects in which friction could be ignored. The presentation of more viscous objects and interactions like rubbing and scraping in virtual reality will necessitate the inclusion of a satisfactory model of friction in the physical models on which the synthesis in based. Inclusion of this important physical phenomenon in real-time acoustic models will be an important issue to study in the future.

The programming issues involved in applying three different modalities with three different time scales in synchrony and in real time in the virtual environment will also be an important issue in future applications.

Finally, in other applications, certainly those in which the users wear a head mounted display, 3D technology for sound will become more and more important. For real live situations the sound comes from and is in general, but not always, perceived as coming from the location where it is generated. Especially in environment with a limited number of speakers it will not always be easy to present the sound that the user perceives is as coming from where it is supposed to be generated.

5.3. Proposed sound technologies for further examination within the SATIN project

In the starting phase of the project, the sound synthesis algorithms will be implemented in MAX/MSP. MAX/MSP is a modular graphical multi sensory programming environment in which the parameters of the sound synthesis algorithms can interactively be varied according to the changing input from a number of different sensors. In this very flexible programming environment the appropriateness and the naturalness of the sounds can be evaluated. This will show both the feasibility of the sound synthesis system and its contribution to the intuitiveness and perceived naturalness of the multi sensory system. Its disadvantages are that the sounds produced by MAX/MSP may not be well specified. and that prediction of the users' movements - necessary to obtain synchrony between sound, image, and haptics - may be impossible resulting in unacceptable time delays between the presentation of the sound on the one hand, and the visual and haptic events on the other. Furthermore, a separate computer is necessary to run the MAX/MSP environment.

The MAX/MSP environment will be used to define the sounds and to tune the parameters of the synthesis algorithms, so that they fulfill the requirements of naturalness and intuitiveness. The sounds must represent not only the material properties such as its inertia, its stiffness, its viscosity, and its elasticity, but also the effort with the material is shaped and its surface properties such as the roughness of the surface. Due to the modular and graphical structure of MAX/MSP, this can be explored very efficiently without the complexities of timing, memory allocation, and multithreading associated with directly programming in C++. Based on the outcome of these experiments, when we know exactly what requirements must be fulfilled as to realism and timing of the sounds, the synthesis algorithms will be implemented within the SATIN environment in C++, so that they can be integrated in the multi sensory environment. Predicting the movements of the user will be an important aspect of this implementation. This will be necessary to obtain an exact timing of the sounds in respect of the actions and gestures of the users. The auditory modality is pre-eminently a timing modality requiring both a high sampling rate, at least approximating the Compact Disk sampling rate of 44100 Hz, and an accurate timing. The associated problems resulting from this issue and the possible solutions are discussed by Pai (2005).

5.4. References

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6. Visualization technology

This section presents an update of the state of the art in the domain of visualization technology. First, we present the Head Mounted Display technology, including a description of available optics, head fixation and interfaces concepts. Several displays of this type have been developed and are reported in Appendix B of this document. Then, some other technologies that may be of interest for the project are presented: projection based devices, the more recent holographic technology and the workbench technology. These visualization technologies may be considered for being integrated in the architecture of the SATIN system.

6.1. Head Mounted Display (HMD) technology

Head-mounted displays provide several capabilities that conventional displays (direct viewed displays, including handheld displays) cannot do. An HMD can be used in many different situations:

- hands free
- stereoscopic viewed
- personal (others can not see the information)
- interactive
- expansive (bigger virtual screen)
- virtual (transparent hovering in the air).

Only an HMD provides the user with an intimate display that can be reactive to head and body movement and surrounds the user with a virtual environment that extends far beyond the confines of the miniature image source.

The HMD is part of a larger system that can include an image generator, a head tracker, audio (microphone and earphone), video-camera and input devices (virtual keyboard, buttons = gesture control). The image generator may be a sophisticated image rendering engine, PC, laptop or an integrated camera. A tracker, which communicates the orientation of the user's head to the image generator, immerses the user in a virtual environment or offers context oriented information. The Input device can include brain-, voice-actuated control or just manual control devices (joystick, mouse etc). Another way is virtual input by detecting fingers or hand moves/positions using the integrated camera.

6.1.1. Available Microdisplays

There are several micro displays available on the market and suitable for NTE applications (Near The Eye) with color image (no monochromes). Several more microdisplays available on the market are designed for video-beamer (projectors). These microdisplays are designed for triple-panel systems (one display for each subcolor RGB) with lower refresh rates. Microdisplays can be divided into three groups:

1. self luminous (OLED)
2. transmissive (LCD) -> backlight illumination
3. reflective (LCoS) -> illumination frontside

Source: http://www.elis.ugent.be/ELISgroups/tfcg/microdis

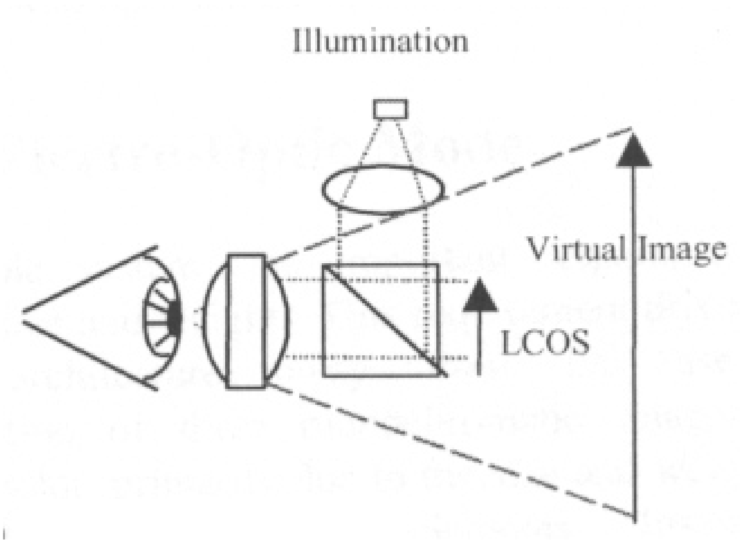
	Producer	Website	Product	Type	Resolution	Color	Refresh rate	Size diag	Contrast	Fillfactor	Power consum	Interface type	Price (single)
1	Brillian Corp	www.brilliancorp.com	Z86D-3	LCOS	800x600	18-bit (24 with LUT)	120Hz	12.0mm	100:1	87%	570mW	Digital	150 EUR
2	CRL Opto	www.crlopto.com	SXGA-R2-H1	LCOS	1280x1024	24-bit	60Hz	22.4mm	200:1	95%		Digital	4.000 EUR
3	eMagin	www.emagig.com	svga+	OLED	852x600	24-bit	85Hz	15.6mm	100:1		395mW	Analog	500 EUR
4	Himax	www.himax.com.tw	HX7500	LCOS	800x600	24-bit	no info		no info			Digital (LVDS)	
5	iMD	www.hkimd.com	iSVGA800C	LCOS	800x600	24-bit	120Hz	15.7mm	400:1	89%	no info		
6	Kopin	www.kopin.com	230K	AMLCD	320x240	no info	no info	6.0mm	no info		5mW		
7	Kopin	www.kopin.com	922K	AMLCD	640x480	no info	75Hz	11.3mm	no info		50mW		200 EUR
8	MED	www.microemissive.com	ME3203	POLED	320x240	18-bit (24 with LUT)	60Hz	7.2mm	no info				10 EUR
9	Sony	www.sony.net		LCD	800x600	18-bit	60Hz		70:1		600mW	Analog	n/a
10	Sony	www.sony.net	LCX033ANB	LCD	800x225	no info	30Hz	11.0mm	200:1		30mW	Analog	
11	Varitronix	www.varitronix.com.	VMD3100	LCOS	1024x768	24-bit	60Hz	20.0mm	700:1	90%			
12	Varitronix	www.varitronix.com	VMD5100	LCOS	1280x720	24-bit	80Hz	17.8mm	1000:1	91%			

LUT: Look-Up-Tables
LCD: Liquid Crystal Display
AMLCD: Active Matrix LCD
LCOS: Liquid Crystal on Silicone
OLED: Organic Light Emitting Diodes
POLED: Polymer OLED

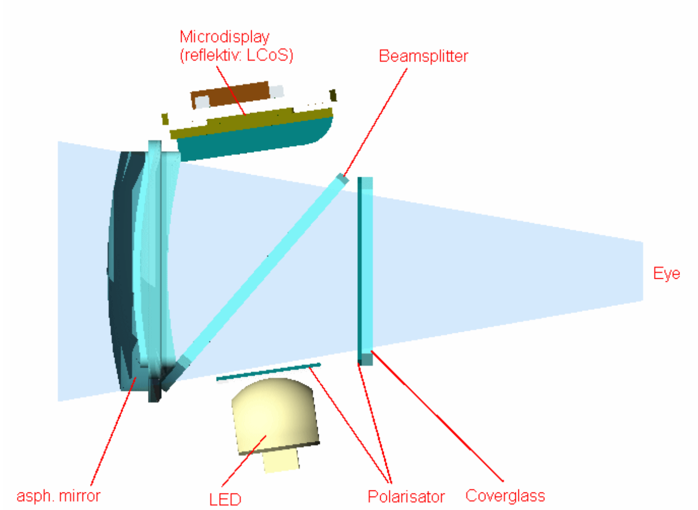
6.1.2. Available optics concepts

Despite the fact that many HMDs have been designed and built over the years, there are really two basic approaches to project the image into user's eyes:

1. One is a new method with a LASER beam writing an image directly onto the retina.
2. The second way is using an optical element to magnify pixel based microdisplays:
   - simple magnifier (eyepiece or concave mirror)

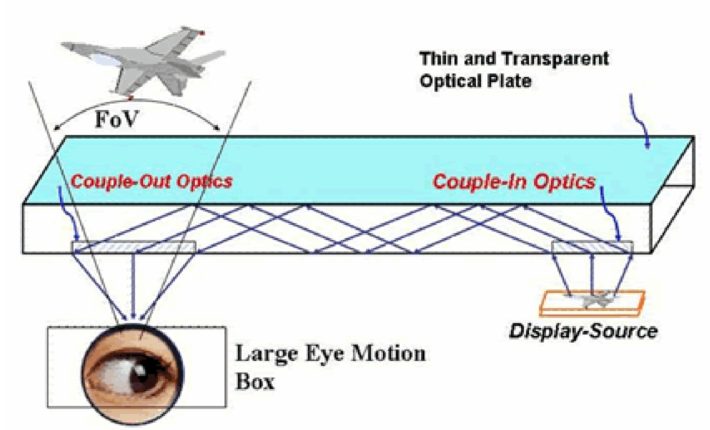


eye-piece



concave mirror

   - compound microscope approaches (multistage optics)



holographic structure (by Lumus)

- a thin transparent plate is directing the image by the use of holographic structure magnified to the users eye.

Another possible classification of HMD's optics is whether it is optical see-through or not (opaque). Some optics like concave mirrors can be used in both ways (back side shutter) or defined by coating on mirror.

6.1.3. Available head fixation concepts

In the past there have been developed five different designs to fix the displays to user's head.

(by Kaiser-Electro-Optics)

- HMD fixed to helmet

- HMD fixed with headbands closed around head (optional overtop, depending on weight)

- HMD fixed with headbands (optional back head or overtop)

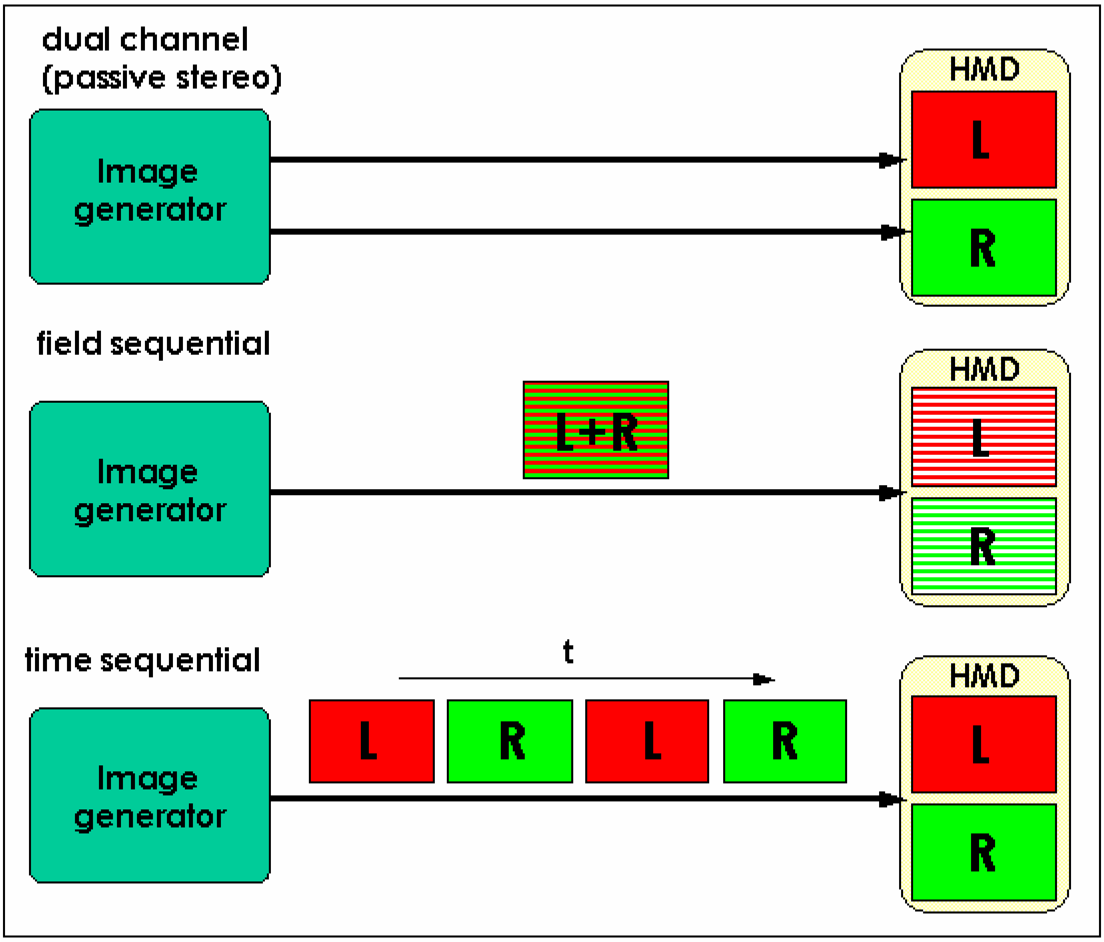
(by MicroOptics)

- HMD fixed to glasses / sunglasses

- HMD in goggles style used like glasses

6.1.4. Available interfaces

Because of the necessary interaction between the user and his environment most HMDs for AR applications must be connected to external computers and video-signals. The current portable computers (PDA or integrated microcontrollers) are mostly not powerful enough and would lead to proprietary solutions, so that a connection between HMD and PC/laptop is needed. This can be done wireless (depending on needed bandwidth) or by cable. The most promising wireless techniques are UMTS and WLAN (depending on distance). The most common techniques for cable based connections for transmitting video signals are Composite-Video/S-Video (analog), VGA (analog) or DVI (digital). To use a stereoscopic HMD there are three principle methods to transmit the video information to the displays:



- The maximum performance offers the dual channel stereo mode. Disadvantages are more cables or thicker cable and more processing power of image generator.
- The field sequential stereo mode (interlaced) offers only half of the possible resolution (vertical or horizontal) but reduces the number of cables and halves the processing output.
- In the time sequential stereo mode the full frames are interlaced by time which reduces number of cables.

The interface standards for transferring the data of tracking camera are PAL (analog), USB2.0 or FireWire (IEEE 1394 / i.Link). For a wireless transmission there can be used analog HF signals or WLAN/UMTS as well, combined with video compression, such as MPEG.

6.1.5. Available interaction and input devices

Because the HMD is used for mobile applications the common input devices like keyboards and mouse are not very useful. They have been replaced by voice control and gesture controlled techniques with the advantage of real hands-free interaction. Additional finger-mouse or arm-mounted keypads can be used, but these types are independent of HMD part.

6.1.6. Available HMDs

Annex B reports an overview of available (on the market) stereoscopic HMDs. None of these offering fully integrated electronic to avoid cables between head-mounted parts and belt fixed control boxes. And none of these HMDs are able to receive video signals wireless. Most of the HMDs have a high power consumption which makes them not well suitable for mobile applications.

6.1.7. Current limitations

Head mounted display technology shows the following deficiencies:

- A major topic for all kind of HMDs is the fact, that current technology does not support a natural way of viewing the virtual environment. For example, all HMDs support a single focal plane only. Obviously this is not consistent with the real-world vision, where objects at different distances are perceived with different accommodation and convergence of the users eyes
- In the past most HMD's were very heavy and uncomfortable to use
- Cables between the head-mounted part and a control box (belt fixed or helmet-fixed) and to image generator are necessary and limiting mobility
- Most HMDs offer limited (very narrow) field-of-view
- The HMDs lack adjustable brightness of the virtual image to be used in a wide range of the real world's ambient brightness
- In a mixed-reality mode only the video-see-through concept is offering full control of the reality images (mutual occlusion). In an optical see-through transparent HMD there is no control of the shimmering reality
- In stereoscopic systems the discrepancy between perception of depth (and convergence) and accommodation to fixed focal plane makes the view not "real"

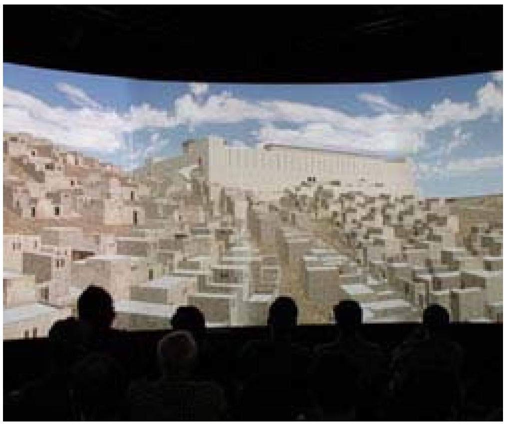
6.2. Projection-based technology

Projection based displays are stationary devices and can be designed in several ways both in terms of geometrical shape of the projection plane itself and system architecture. The size itself of the display influences the interface to the virtual world by filling a wider field of view of the user and allowing him to move more freely within the space. Most projection VR systems are rear projected to avoid the participants casting shadows on the screen. There are a number of advantages in using a projection-based display system. They are typically able to provide high spatial resolution and a large Field Of View (FOV) allowing the user to utilize his peripheral vision. Like monitors they can provide monocular depth cues and, if the user is tracked with enabled stereoscopic vision, the motion parallax cues are even becoming more intense (specifically in the CAVE environment where the parallax is provided by the possibility of the user to walk within the environment).
Concerning stereo it is typically possible to have both active and passive stereoscopic vision. Active stereo vision is based on a system very similar to the one used for monitors. Currently, thanks to high refresh rate projectors it is possible to have stereopsis similarly to what happens with monitors by providing left and right channel images to the same projector and using shuttering glasses. Just a couple of years ago this result was achieved by the use of two projectors and by adding a mechanical shutter in front of the projector synchronically to the shuttering of the glasses. This system was expensive, because of the need of two projectors and specifically designed mechanical shutters and most of all too noisy. Because of this passive stereo-glasses have been developed. They are based on Polarization multiplexing or spectral multiplexing. Polarization multiplexing filters the two separate overlaid images with oppositely polarized filters (one eye is vertically polarized and the other horizontally so that each eye perceives just one image). Spectral multiplexing is a rather old method used since the 60's in cinemas. Basically, this second method displays the two separate, overlaid images in different colors. The glasses use colored filters so that light from any other color than the filter color is washed out (usually blue and red filters).

<u>Fakespace systems</u>
(http://www.fakespacesystems.com/)
CURV™ Immersive, Wrap-around Field-of-View Available Front or Rear Projected.
Popular for its high-impact wraparound images, the CURV™ provides an ideal environment for interactive research, collaboration and presentations. As the original curved screen system to offer either front or rear projection, the CURV is now leading the industry's digital revolution by offering high-brightness, active stereo, DLP™ projection technology. The CURV is scaleable up to a full 360 degrees HFOV and 180 degrees VFOV. Rear projected CURV's are also available with folded optics to minimize overall system footprint.
The CURV solution is ideal for a number of different applications including:

- Seismic interpretation and well planning
- Virtual walk through
- Biotech research

- Computational fluid dynamics
- The CURV comes with a number of feature options including:
- Rear or front projection
- Active or passive stereo options
- Vertical and/or horizontal edge-blending
- Cylindrical or spherical screens



6.3. Holographic technology

Holography is an image-generation technique which can correctly display all of the visual depth cues employed by the human visual system. Electronic holography uses an electronic transducer to create a holographic fringe pattern which generates the desired image. As with stereoscopic displays, holographic displays are most useful for situations in which three-dimensional objects are within arm's reach of the viewer. Holographic displays also provide a path to a collaborative environment in which each viewer will have the scene correctly displayed without wearing any additional hardware. In the past ten years, prototype interactive electronic holographic display systems have been fabricated by the MIT Media Laboratory.

The principal requirements of an interactive electronic holography system are the ability to calculate and display the correct holographic fringe pattern in real time. Calculating the fringe pattern for a holographic display is hundreds of times more difficult than rendering a two-dimensional display image. It is estimated that off-the- shelf hardware capable of rendering holograms in real time is still years away.

The computing requirement for a cubic centimeter of holographic video is roughly one billion operations per second. Rendering a holographic apple requires roughly a cubic liter, or 1000 times more computing capacity. The desired transducer for holographic video is a phase-modulating device with 256 output levels and a quarter-micron pitch. Current liquid-crystal-on-silicon spatial light modulators have a pitch around 10 μm, or 40 times larger than is required.

<u>Holografika</u>

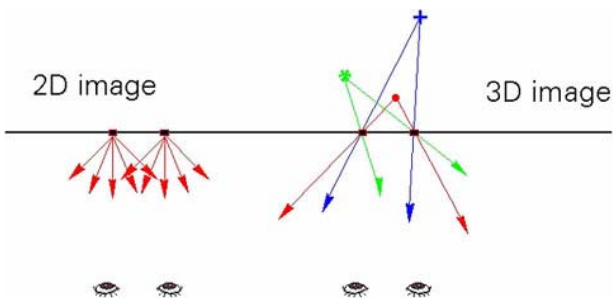
(http://www.holografika.com/)

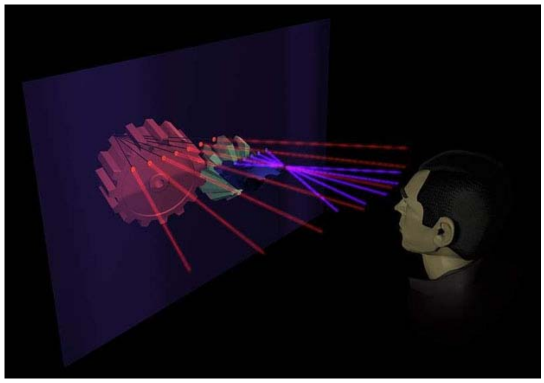
Holografika supplies a proprietary 3D holographic display technology, called the HoloVizio™ system, which provides multiple viewers with a natural 3D view without the need for special glasses or tracking equipment.

How does HoloVizio™ work? Well, for starters, it is not the same as so-called auto-stereoscopic 3D systems, developed by companies such as Sharp, which involve showing a viewer two slightly different 2D images – one for the left eye and one for the right eye – and the viewer's brain fusing them to produce a single perceived 3D image.

Holografika's approach aims to mimic that of a viewer looking straight out of a conventional window - which is essentially a 2D object – but nevertheless perceiving the outside environment as a perfect 3D image. In this situation, the viewer perceives a 3D effect because the light patterns at each point on the window change subtly according to what is behind it and the angle it is being viewed.

Consequently, HoloVizio™ involves a viewer looking at a 'digital window'. Tibor Balogh, Holografika's CEO and Founder, explains: "It uses a holographic screen. When beams inside the device strike the screen, each point of the holoscreen is able to emit light beams of a different colour and intensity in different directions."
Since 2004, the company has been supplying HoloVizio™ displays for scientific visualisation and medical applications as well as automotive computer-aided design.
In 2005, the company received an undisclosed first round of investment from Hungary's largest electronics manufacturer, Videoton Holding. "Today, Holografika is looking to raise 12m euros in order to finance the expansion of international sales and distribution activities," says Balogh.
Holografika is currently involved with three IST funded projects focussed on holographic developments. The company has been leading the 3.7m euro COHERENT project which has created a new networked holographic audiovisual platform that can support real-time collaborative 3D interaction between geographically-distributed teams. Holografika produced especially a 1.8m sized high-resolution display that was successfully evaluated within a collaborative medical visualisation system (COMEDIA) and a collaborative design review system for the automotive industry (COLLAUDA).





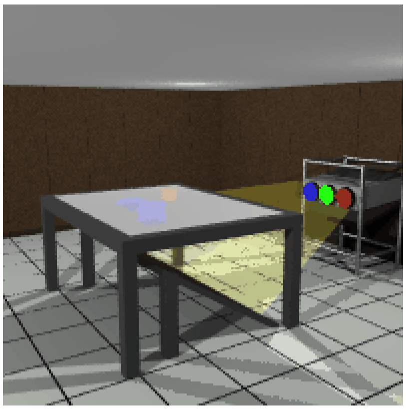
6.4. Workbench technology

Several technologies based on the tabletop metaphor supporting 3D visualization and interaction have been recently developed. Their aim is intensifying the perception of models and data, and supporting collaborative work among several users. Usually, the user stands in the real world and looks into a virtual world which is projected on the screen of the workbench.

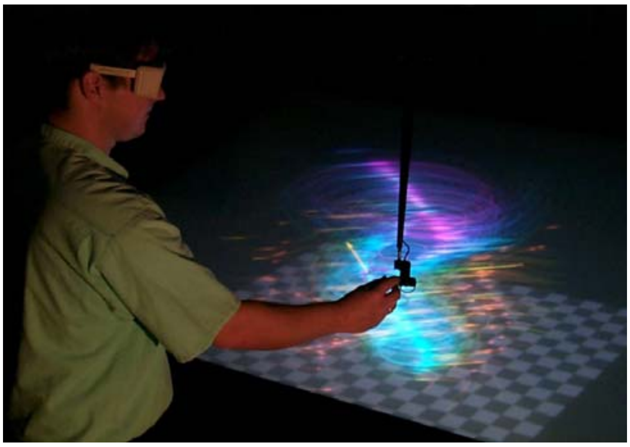
<u>Responsive Workbench</u>
(http://graphics.stanford.edu/projects/RWB/)
The *Responsive Workbench* is a 3D interactive workspace originally developed by Wolfgang Krueger at GMD. Computer-generated stereoscopic images are projected onto a horizontal tabletop display surface via a projector-and-mirrors system, and viewed through shutter glasses to generate the 3D effect. A 6DOF tracking system tracks the user's head, so that the user sees the virtual environment from the correct point of view. A pair of gloves and a stylus, also tracked by the system, can be used to interact with objects in the tabletop environment.
Our current research involves extending the workbench environment to more efficiently support interaction, visualization and collaboration.

- To support interaction we have been: researching techniques for two-handed manipulation, developing workbench tools or widgets, and investigating various other interface metaphors appropriate for the workbench.
- To support collaboration we (working with FakeSpace) have developed a two-viewer version of the system. The two-viewer version is capable of simultaneously tracking the head position, and displaying a stereo pair of images, for two users.
- To test the effectiveness of using the workbench for visualization, we are currently exploring several different application areas, including architecture, scientific visualization, and medicine.

We are also researching basic issues involved in building environments such as the workbench: hardware, calibration, and rendering.

The Visual HapticWorkbench
(http://www.cs.utah.edu/~ikits/publications/Brederson_PUG_00.pdf)
Multimodal interfaces have been shown to increase user performance for a variety of tasks. We have been investigating the synergistic benefits of haptic scientific visualization using an integrated, semi-immersive virtual environment. The Visual Haptic Workbench provides multimodal interaction; immersion is enhanced by head and hand tracking, haptic feedback, and additional audio cues. We present the motivation and design goals for this system, discuss its current implementation, and describe some initial applications. Preliminary results indicate that visualization combined with haptic rendering intuitively conveys the salient characteristics of scientific data.

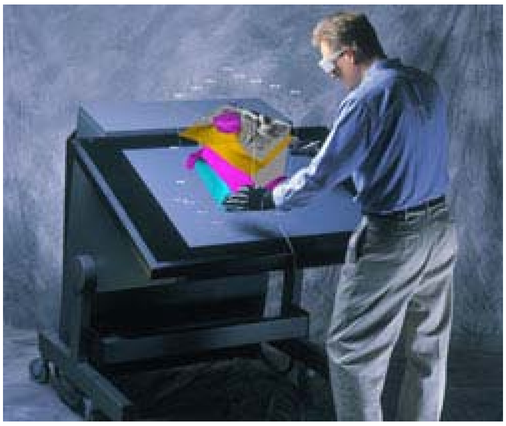
Fakespace systems
(http://www.fakespacesystems.com/)
M1 Desk™ Desk-Side Collaboration and Virtual Modelling Station
The M1 Desk is a versatile, permanent or portable virtual modelling station ideal for development and engineering review applications. While small enough to fit into an office, the self-contained M1 Desk offers a large 44" diagonal high-resolution visualization screen. The desktop angle is adjustable to suit any work style or viewing preferences. Optional head tracking facilitates the correct perspective of stereo images as you move naturally around the desk. The optional tracking systems also facilitate the use of various interaction devices such as a stylus, virtual wand or glove-based technologies. The folding design allows for easy room-to-room movement, storage or transport.
The M1 Desk contains a number of features including;

- Single lever adjust for variable screen angles
- Fast and reliable set-up - less than 30 minutes
- Compatible with a variety of computing platforms

The M1 solution is ideal for a number of different applications including;

- Component parts design
- Seismic Modelling

- Architecture
- Virtual Prototyping
- Anatomy and Life Sciences applications such as molecular modelling and protein analysis



7. Human Computer Interaction

Improving the efficiency, friendliness and ease of user interaction with multimedia devices is one of the main goals of research in human–computer interaction (Swapp et al 2006). This section aims to describe the relevant human computer interaction research that applies to tangible and sound interfaces. It is necessary to consider these in the context of the technologies and applications for which they have been developed – for example, in a shape modelling application, the visual information coupled with any tangible or sound feedback will have a critical influence on the usability, ease of interaction etc. Therefore a section on the design of the visual interface is also included.

7.1. HCI characteristics of tangible interfaces

Tangible "bits" were an attempt to join the gap between cyberspace and the physical environment by making digital information (bits) tangible (pg 23) (Ishii 1997). The authors decided that this could be achieved by using interactive surfaces by transforming each surface into an active interface between the physical and virtual worlds. This paper also mentions the importance of the background and the periphery of the VE. The authors feel that the periphery provides important information, and if anything unusual is noticed then it becomes focused on. The transition between background and foreground using ambient media and graspable objects is a challenge. They also found that the use of light, shadow and optics were compelling for interfaces spanning virtual and physical space.

Tangible user interfaces (TUIs) are characterized by: some input event occurs usually performed by the user with their hands, a computer system senses the input and then alters its state and a system provides feedback and the feedback is a change in the physical nature of some object (Fishkin 2004).

TUIs and tangible interaction are increasingly gaining currency within HCI (Hornecker 2006). From the literature Hornecker (2006) sub-divided tangible interaction into the categories of data-centered view, expressive-movement-centered view and space-centered view. The expressive-movement-centered view is an emerging 'school' in product design which encompasses more than form and appearance that places more emphasis on bodily interaction with objects.

Hornecker's framework (2006) on tangible interaction is structured around four themes which are

- tangible manipulation:
- spatial interaction,
- embodied facilitation and
- expressive representation.

These themes are all interrelated but offer different perspectives on tangible interaction.

The key HCI characteristics of tangible interfaces, in the context of the SATIN project, can be summarised as:

- The realism and usefulness of the feedback given by the haptic system in relation to the design task being undertaken
- The extent to which the tangible interface enhances the performance of users in a design task
- The interaction between the haptic/tangible interface and the other interfaces (sound, visual) being presented to the user

7.2. HCI characteristics of sound interfaces

What it is about sound that influences user performance, attitude and behaviour?

The key HCI characteristics of sound interfaces, in the context of the SATIN project, can be summarized as:

- The realism of the sound in relation to the sound feedback that would be obtained during real world design
- The usefulness of (not necessarily realistic) sounds to enhance design performance

- The interaction between the sound interface and the other system interfaces (haptic and visual)

Blattner et al (1989) described the use of earcons, which are audio messages used in the user-computer interface to provide information and feedback to the user about computer entities. Earcons included messages and functions, as well as states and labels. However, there were issues with learning and remembering earcons.
Sounds and motions in virtual environments sound should be integrated. If sounds and motions do not have the proper correspondence then the resulting confusion can lessen the effects of each (Hahn et al; 1998). To overcome this problem Hahn et al (1998) describe the system of a functional representation of sounds called timbre trees.
Van den Doel and Pai (1998) put forward a general framework for the simulation of sounds produced by colliding physical objects in a VR environment. The computed sounds are dependent upon the material of the body, its shape and the location of the collisions.
Bormann (2005) examined the impact of the utility of audio spatialisation versus the fidelity of audio spatialisation to the entity of presence. The subjects searching for the active sound source was detrimental to performance but this group had the largest increase in presence scores over the baseline experiment. In addition having the sound source active positively impacted the assessment of the audio whilst negatively impacting subjects' assessment of the visuals.

7.3. Application of multimodal interfaces to product design

One of the application domains where multimodal free-hand-based haptic and sound interfaces would bring great benefits is in the conceptual phase of product design. As the conceptual design of a new product starts from an initially incomplete and imprecise mental representation the designer has in mind regarding the object shape. The main object of the SATIN project is to develop a new generation of multimodal and multi-sensory interfaces which provide natural and adaptive tools to support users' intentions and behaviour, supporting free-hand interaction with virtual shapes which consist of "multimodal interface based on a fusion of force feedback, sound and vision to enable representation of global and local properties of shape and material, which can be perceived statically or dynamically during exploration and modification of digital shapes performed by users through free-hand, unconstrained robust and ergonomic interaction".
Novel haptic and tangible interfaces allowing users to modify digital shapes through free-hand interaction which aims at exploiting users' dexterity and skills when physically interacting with materials (SATIN working group 2005).
The key requirements of these interfaces (taken from SATIN December meeting 2006) in the context of product design are:

- Reduce development time for a product
- Allow easier corrections of already make 3D models
- Reduce development costs
- Provide greater client satisfaction
- More flexibility

7.4. Interactive system design requirements

7.4.1. Context of use consideration

It is vital to consider the context in which the VR system should be used. The following considerations should be made:

- Group vs. single user: whether there will be a number of people involved in viewing or interacting with the system. The likely SATIN model is that a single user will be interacting with the system, but it is possible that others will be gathered round viewing the designer whilst they are completing their design. This will have a number of implications – they may be talking to the designer, thus influencing the user's perception of any sounds produced. The external viewers may be able to hear the sounds emitted by the system, depending on the sound technology used, but will not receive haptic feedback from the interaction mechanism.

- User expertise and role: this will influence the skill that the user has, both in their expertise as a designer and their expertise in use of interaction devices.
- Training requirements and potential: whether the users are trained in use of the system, and how long they have to get used to the type of feedback they receive from the system before being required to actively use the technology as a design tool
- Language familiarity: whether any of the visual interface elements involve written text – if so, whether this is presented using specific terms that require either technical or design based knowledge, and whether the language used is one that is actually spoken by the user.

7.4.2. Display requirements

Whilst the focus of the SATIN project is on tangible and sound interfaces, a visual display will still be used. Therefore, the effects of this display alone and in particular the interaction between the visual display and other system elements must be considered.

Auto-stereoscopic 3D displays
A headset is not always necessary to achieve a 3D image as 3D display systems are now able to support an auto-stereoscopic, no-glasses 3D experience with a good image quality. There have been advances in auto-stereoscopic 3D display for desktop users (Holliman, 2006) due to the ability to combine micro-optics and flat panel displays which is combined with desktop image processing and 3D computer graphics systems. The right and left views are seen by the viewer without the need for glasses. Three main types exist which are the two view auto-stereoscopic displays, multi-view auto-stereoscopic displays, and tracking two view auto-stereoscopic displays. However, 3D images are more impressive and give depth perception, spatial localisation, breaking camouflage, surface material perception, and surface curvature appreciation. Surface material perception is important as this can utilize reflection and refraction to make an object appear more real.
As the SATIN project is designing products professional then the 3D aspect will be preferable. There are two main methods of providing the user with a 3D image:
- Head mounted displays (with the display technology integrated within a headset)
- Projection displays viewed via polarizing or shutter glasses

Head mounted displays
A typical head mounted display (HMD) consists of a helmet with two small displays (CRT or LCD) and an adjustable lens system. Stereoscopic viewing is achieved by presenting separate overlapping images to each eye.
Advantages for HMDs are that:
- Users are visually insulated from the real world and feel physically immersed
- More modern HMDs are much smaller, and therefore much lighter to wear.
- Head movement tracking can be incorporated into the display
- The movement of the participant viewpoint is intuitive

The disadvantages are that:
- There is limited field of view
- The resolution of the displays can be poor
- Physical discomfort may result from the wearing of the headset
- Interaction can be difficult as a participant may not be able to see their arms and hands (VIEW IST-2000-26089 July 2001).

The latter point is an important one which was brought up at the SATIN meeting in December 2006. If an HMD is worn then the user will have problems interacting with the haptics, although this could be minimized, with the appropriate use of sound. One solution suggested at the December 2006 meeting was the use of newly developed ‘see through’ HMDs, which will be available from next year.
Headsets vary in weight but some can be heavy, for example the Cybermind hi-res weighs 800g. In some HMDs the weight distribution is not even (the front is heavier) which can make it

uncomfortable to wear after a short period of time, even 30 minutes. Designers have specified that it would be preferable to be able to achieve at least 4 hours of working time on the SATIN system, but have only managed around 45 minutes with current HMDs (SATIN meeting December 2006) Lighter binocular headsets are now available but do not always cater for the size variability of heads. Off the shelf headsets tend to have been designed for shorter periods of 3D game playing as opposed to prolonged use at work.
The optics presentation within the HMD should be considered as the use of prisms should be avoided, especially base in prisms as these cause more visual discomfort (Howarth 1996).
It is also useful to have the ability to vary inter ocular distance/interpupillary distance with the HMD to allow for variability in individual's distance between each eye.

7.4.3. Projection screens

In recent years the focus of display technologies has moved from HMD based systems to projection displays. Projection displays have the advantage of the potential for collaborative viewing and interaction and are an attractive financial option as the technologies can often have multiple uses rather than requiring expensive purchase of dedicated VR technologies (Nichols et al, 2000).
In a typical projection system, the VE is projected onto a free-standing or wall-mounted projection screen via conventional three-tube video projectors. The VE is usually manipulated and interacted by one participant with the remaining individuals as passive observers. Navigation and interaction usually take place using standard PC input devices, but if required more sophisticated devices can be used (VIEW IST-2000-26089 July 2001).

Stereo images can be achieved using projection systems by using:
1) Active stereo projection which uses one projector per wall, which is able to switch the displays of the image for the left and right eye 60 times per second. The participant is required to wear shutter glasses with inbuilt electronics that actively alternates the left or right eye.
2) Passive stereo projection which required two projectors for each projection wall. The images for the left and right eye are displayed simultaneously. Each of the two projectors has a polarisation filter, one for vertical and one for horizontal polarisation, in front of the lens (VIEW IST-2000-26089 July 2001).
A projection augmented model (PA model) is a type of haptic augmented reality display which consists of a real physical model, onto which a computer image is projected to create a realistic looking object. A PA model creates the illusion of actually being the object that it represents, as opposed to a white model and a projected image. Users can physically touch the surface of a PA model with their bare hands, which has experiential value for the types of applications for which they are being developed. The downside is that, the majority of PA models does not provide haptic feedback for material properties such as texture, and do not feel correct when they are touched. In addition, most PA models are front-projected which means the projected image appears on the back of the user's hand, and their hand casts a shadow on the display. Previous research has found that touching this type of PA model reduces a user's sense of object presence. It was found that object presence was significantly higher when correct haptic feedback for material properties was provided; however eliminating the visual projection problems rarely affected object presence. These results have implications for the direction in which PA model technology should be developed. They also have implications for theory on how the haptic and visual senses contribute to a person's sense of object presence, and indeed presence (Bennett 2006)

Desktop system

A typical desktop system uses a standard CRT monitor as the display device. The user is not surrounded by the VE but has access via a window onto the VE. Interaction is achieved via input devices such as the SpaceMouse or multi-axis joysticks. Or standard PC input devices can be used if the VE interface is designed with icons which allow the user to navigate or participate in the VE (VIEW IST-2000-26089 July 2001).

7.4.4. Interface design requirements

Visual display guidelines (including interface design, e.g., menus)

A number of studies have identified the influence of the design of the visual interface and display on user performance. A number of elements of the visual display will influence user performance and use, including resolution, colours, use of textured images and patterns, lag, frame rate and detail. The level of influence of these elements will depend on the task being performed – for example, if a design task includes fabric, it is important that the detailed material properties of the fabric are clearly displayed, to show the hang and folds in the fabric. If the task involves design using reflective materials, such as metal or glass, the reflection needs to be represented in some manner. It is important to note that expert designers may not need accurate display of the reflective properties in order to produce effective designs – for example, using stripes on an image may be effective at conveying curved surfaces.

There is a fundamental challenge when viewing CAD models. In order to provide accurate design information for use in computational manufacturing technologies a CAD model, and its associated accuracy in measurements, is required. However, CAD models are often highly complex in terms of the number of facets included in an object. This high number of facets can present problems in real time rendering systems, therefore it is often the case that an object that is viewed within a visualisation system is simplified in some manner. In addition, CAD models often do not include textured images or have reflective properties – these elements are likely to be important in providing effective feedback to the user during the design process.

In addition to the visual display qualities, it is important to consider the design of the interaction metaphors, menus and input devices (e.g. push buttons, mice etc.) which may be used in conjunction with the haptic input device. Figures 1 and 2 show the overview of visual display design issues identified from the experimental programme conducted in the VIEW of the Future project (IST- 2000-26089).

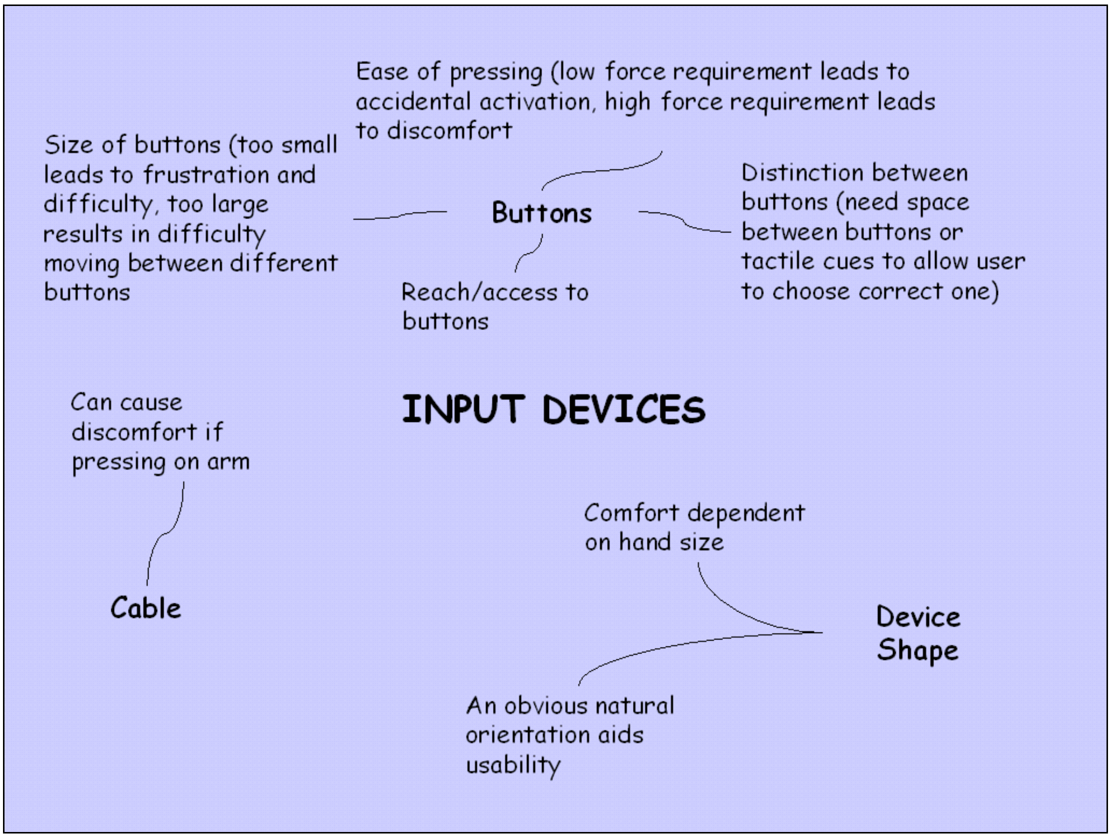


Figure 1 (taken from VIEW of the future IST-2001-26089).

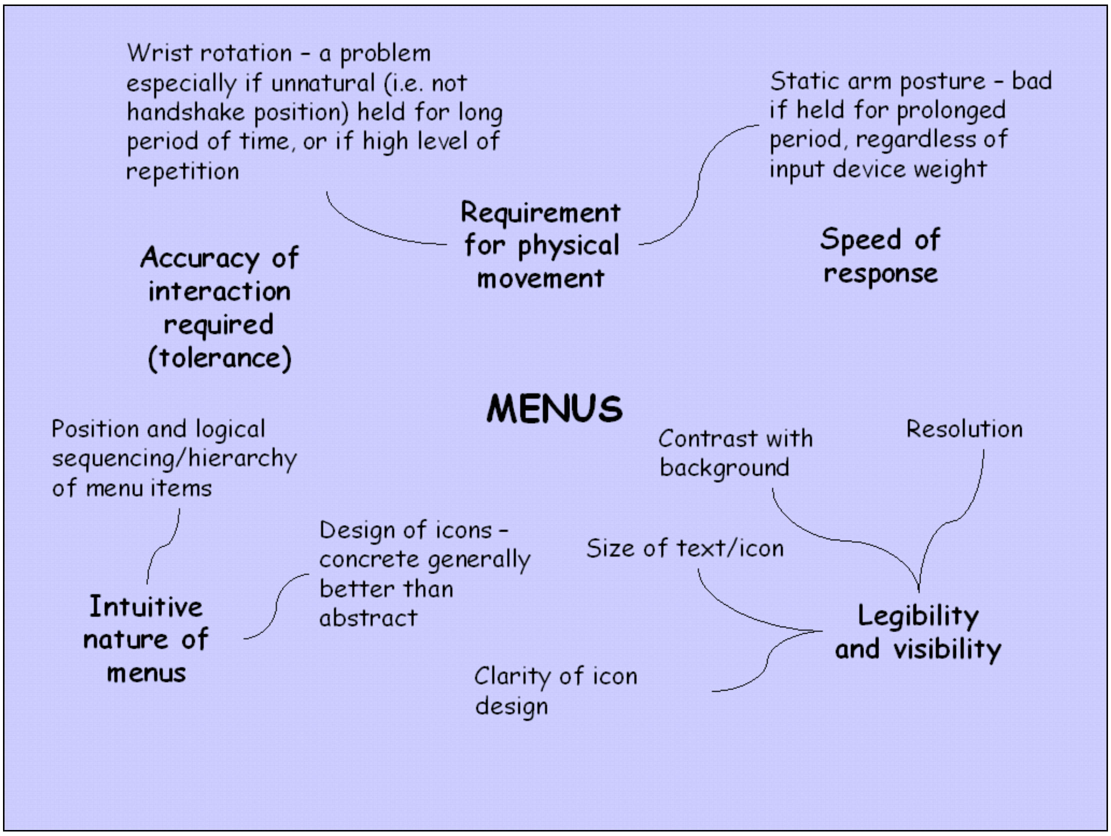


Figure 2 (taken from VIEW of the future IST-2001-26089).

Sound display guidelines

The use of sound to facilitate the design process is a key element of the SATIN project. The current methods of design used (e.g., clay modelling) have limited sound feedback as part of the process, therefore it is assumed that sound will provide additional information or feedback to the user that would not normally have been received. This sound feedback may provide information about the resistance of the material, the material properties of the simulated materials (e.g. metal, wood or glass), and extensive testing will be required to identify user perception of these sounds. It may be that it is appropriate therefore to develop artificial cues to material properties where none already exist (e.g. in clay modelling) – for example, an increasing or decreasing tone pitch could indicate the underlying depth of the material being sculpted.

Contact sounds can provide important perceptual cues in virtual environments. The relationship between material perception and variables that govern the synthesis of contact sounds has been investigated (Klatzky et al; 2000). Klatzky found that shape-invariant, auditory-decay parameter was a powerful determinant of the perceived material of an object. The results support the use of a simplified model of material in virtual auditory environments.

Speech and interface interaction

Speech is not the intuitive interface it was once thought to be. In some areas (such as ATC) speech has been developed as the primary means of communication but as an input device it remains awkward to use. Therefore, speech input should be regarded as a tool, as with any took, users must be trained to use it effectively and it must be designed to support users (Stedmon, 2005).

If speech activation is to be used in the SATIN project then it was recommended that the number of words used for specific tasks should not exceed 10 and even with a limited number of words some users will fail to be able to access the interface (Jorge, SATIN meeting December 2006).

If interaction with the interface was via a ‘push to talk’ system, then the user may as well interact directly with the interface (Stedmon, SATIN meeting December 2006).

Haptic display guidelines

The realism, detail, mapping of the haptic feedback to visual interaction needs to be considered.
Chen and Sun (2006) proposed a novel body-based haptic inter-action model that simulates the intrinsic physical properties of the tool and virtual objects during the haptic interaction. When tracing the haptic tool interacting with objects, the body-based force evaluation model based on Hertz's contact theory including both frictional and frictionless contacts. The physical properties of different object materials expressed by Poisson's ratio and Young's modulus are involved to simulate the realistic touch perception between the haptic tool and objects. The results have shown a satisfactory performance of the body-based haptic model which were developed while interacting in touch-enabled virtual environments.
Borst and Volz (2005) have developed a haptic feedback technique that combines feedback from a portable force-feedback glove with feedback from direct contact with rigid passive objects. This approach is a haptic analogue of visual mixed reality, as it can be used to haptically combine real and virtual elements in a single display. The authors evaluated the approach for interactions with buttons and sliders on a virtual control panel. This approach resulted in better task performance and better subjective ratings than the use of only a force-feedback glove. Visual feedback was then degraded and the combined approach resulted in better performance than the glove-only approach and in better ratings of slider interactions than both the glove-only and passive-only approaches.
The study by Choi and Tan (2005) demonstrated a significant increase in the maximum stiffness for stable haptic texture rendering. They also reported a new type of perceived instability, aliveness, that is characterised by a pulsating sensation. Their results underscore the important roles played by environment modelling and human haptic perception, as well as control stability, in ensuring a perceptually stable virtual haptic environment.
Haptic collaborative virtual environments which also have touch can be networked to allow shared experience of the interaction. The main obstacle to overcome was the latency-induced instability of the system but this has been achieved with a surgical-simulation application over 3 continents (Gunn et al, 2005). Hamza-Lup and Rolland (2004) proposed a novel criterion for categorisation of distributed MR/VR systems and present an adaptive synchronisation algorithm for distributed MR/VR collaborative environments. Significant network latency existed but their results showed that for low levels of update frequencies the dynamic shared state can be kept consistent at multiple remotely located sites.

Dosher and Hannaford (2005) investigated the ability of subjects to detect small haptic effects and the associated gains in task performance with various configurations of haptic stimuli. Results indicated that rough (sawtooth) haptic icons are more easily detected by a human subject than smooth (sinusoidal) icons of the same size. Transient vibrotactile cues may contribute to these observations.

Integration of visual, sound and haptic interfaces

Biocca et al (2001) investigated the role of intermodal integration in presence and looked for evidence of intermodal integration in the form of cross-modal interactions-perceptual illusions in which users use sensory cues in one modality to "fill in" the "missing" components of perceptual experience. One form of cross-modal interaction, a crossmodal transfer, is defined as a form of synesthesia, that is, a perceptual illusion in which stimulation to a sensory modality connected to the interface (such as the visual modality) is accompanied by perceived stimulation to an unconnected sensory modality that receives no apparent stimulation from the virtual environment (such as the haptic modality). A path model of the data suggested that this cross-modal illusion was correlated with and dependent upon the sensation of spatial and sensory presence. The authors conclude that this is evidence that presence may derive from the process of multimodal integration and, therefore, may be associated with other illusions, such as crossmodal transfers, that result from the process of creating a coherent mental model of the space. It is suggested that this perceptual phenomenon might be used to improve the user experiences with multimodal interfaces, specifically by supporting limited sensory displays (such as haptic displays) with appropriate synesthetic stimulation to other sensory modalities (such as visual and auditory analogs of haptic forces).

The aim would be to minimise or preferably eliminate time delays and aim for total integration of vision and sound and control with the haptic interface. It was suggested at the SATIN meeting in December 2006 that it would be acceptable to reduce the time lag for haptic use to 10ms.
It is important that any limitation to update rate is considered in relation to presence – it is known that if any elements of poor system performance (e.g. lag) are noticeable to the user then this may cause a "break in presence" (Slater et al.,) However, many presence theories assume that a key component of presence is "realism" – in fact, it may be the case that in the SATIN system, if a sound is useful, it may enhance presence and user performance, but may not actually be realistic. This is something that will require further investigation during the SATIN project and system evaluation.

7.5. Practical considerations in technology design

7.5.1. Context of use

The major consideration with implementing the SATIN technology is the types of techniques that are currently used by designers. Designers are highly skilled and able to visualise designs highly effectively, they also develop specific modelling techniques based on the traditional methods that they use for prototyping. This results in some practical considerations, such as whether the hardware need to be easy to clean – this is important even if not in a 'wet' area but if headsets or head mounted viewing devices are shared it is still necessary to clean them with an appropriate product.

7.5.2. System compatibility

E.g. with other used technologies e.g. CAD integration

7.6. Human factors issues

7.6.1. Posture/comfort

The proposed design for the SATIN technology requires the user to be standing whilst performing the design task. Standing work is known to be associated with a number of postural discomfort symptoms if the period of use is extended.
The most commonly reported symptoms appear to be discomfort, fatigue and swelling in the legs. Workers required to spend too much time on their feet are at greatly increased risk of pain and discomfort affecting feet, shins and calves, knees, thighs, hips and lower back. A high prevalence of varicose veins of the lower limbs was found in women who were on their feet for the majority of the day (Stvrtinova et al 1991). Ryan's (1989) work on supermarket workers found a positive and significant correlation was found between the proportions of time spent standing, and symptoms in the lower limb and foot.
A 2002 review of 17 studies of the health risks associated with prolonged standing concluded these included chronic venous insufficiency, musculoskeletal pain of the lower back and feet (O'Neill 2005) indicated that a "prolonged time in an upright posture at work constitutes a risk factor for the development of hypertension comparable to 20 years of aging, which in turn is one of the accepted major risk factors for the development of cardiovascular disease". Buckle et al. (1986) recommend that workers spend no more than 30 per cent of their working day standing.
If standing at a workstation is necessary then it is important concrete flooring is avoided. Materials which offer flexibility are preferable, for example, wood, cork, carpet. Anti-fatigue matting is available and use of appropriate footwear (with cushioned insoles and heels a maximum of 5cms) O'Neill 2005.

It is also important to consider the influence of the task and interface design on the posture adopted – for example – if it is difficult to manipulate the object easily within the visualisation system the user may make more head movements if wearing a tracked viewing device. These increased head movements may lead to unnatural postures being adopted, and place additional strain on the neck, shoulders and back.

7.6.2. VR-induced sickness and postural instability

A number of studies have shown that sickness can result from viewing virtual reality displays. The factors influencing sickness are associated with the display technology, environment, task circumstances and individual characteristics (Nichols et al., 1997). The VIRART team at the University of Nottingham has conducted a series of studies examining the sickness effects experienced by users of HMD, projection and desktop systems (Cobb et al., 1998; Nichols et al., 2000). Overall, it was found that approximately 80% of participants tend to experience some level of sickness, but for the majority these symptoms are mild and subside quickly. For about 5% however, symptoms can be severe and lead to them being unable to continue using the technology.

As the task in the SATIN project is related to design of objects there is likely to be a lower level of optic flow (one of the major potential contributors to VR-induced sickness) therefore it is anticipated that sickness levels may be lower than with some environments. However, in any situation where there is perceived motion on the part of the user (which is likely to occur with any tracked head movements, and particularly when large objects such as cars are being designed), sickness may occur, particularly for those members of the population who are particularly susceptible.

The main recommendations from the VIRART work when implementing VR in the workplace are:

- Education about potential negative effects of VR use, with the aim of minimising anxiety about the experience
- Designing VEs so that the minimum level of symptom-provoking elements is present for susceptible individuals
- Informing participants about appropriate behaviour strategies that may minimise negative symptoms but not detract from their experience of using the VE, including training in use of input devices
- Where possible, allowing participants control over their movement around the VE
- Monitoring of VR participants, and providing assurance that they may terminate their period of exposure at any time (this point should particularly be emphasised for susceptible individuals)
- Education of people responsible for monitoring VR participants about possible physiological signs and behaviors that participants who are experiencing negative symptoms may exhibit (e.g. sweating, pallor, fidgeting with HMD, looking away from display, closing eyes)

(Nichols et al., 2000). It is also recommended that exposure time is limited to sessions of 30 minutes, although this recommendation may depend on the type of display technology, environment and task being conducted.

7.6.3. Ocular side effects

'just because you can see a stereoscopic image comfortably does not mean everyone else can' (Holliman, 2006). Holliman reports this is because the more you use stereo effect the more adapted you become. However, it is important also to consider factors such as level of stereo-acuity which varies from person to person, presence of any squint (turn in the eye) or amblyopia (lazy eye) which means no 3D vision (3-5% of the population have a lazy eye) or the presence of a decompensating deviation which will be exacerbated by being dissociated with the head mounted device. In fact following immersion within a stereoscopic HMD it was found that a shift in heterophoria occurred, in that it increased (Wann et al, 1995). Wann et al (1995) thought that a simple solution to the avoidance of visual stress in not apparent, especially when a large stereoscopic depth range is required for conventional binocular designs.

7.7. Equality and diversity

7.7.1. Hearing deficits

Literature regarding the experience of the absence of sound is rare (Murray et al, 2000 pg138) but sound has proved to be the most reliable indicator of presence in the studies of collaborative VEs (Murray et al, 2000).. Murray's research found that the users in the experiments felt less secure, less aware of their movement and less confident. But these finding were related to collaborative environments and replicated only moderate hearing loss.
Variable volume control would be useful to cater to individuals requirements, in addition to allowing for single user work or the user collaborating with workers not immersed in the VE.

7.7.2. Visually deficits

Some headsets have incorporated lenses for correction of refractive error, but these are for straight forward prescriptions. If the glasses prescription is very high or complex the user will still not be able to see clearly.
Reading glasses, in those users who are presbyopic may even be required to be worn depending upon if any elements of the interface require clear vision at close to.
Wearing a headset with glasses causes problems as the glasses frames interfere with the fit of the glasses and may even scratch the surface of the glasses.

7.7.3. Motor problems

Medical problems such as arthritis or RSI depending upon how much repetitive work are involved with the design process. Some people may not have excellent fine motor skills.

7.8. Conclusions

If virtual systems are to be effective and well received by their users, then considerable human-factors research needs to be undertaken (Stanney et el, 1998). The aim is to produce a system in which as many users as possible are able to use it, for as much time as possible with minimal symptoms. The system should allow for variabilities in heights, vision, hearing, skills of using the interface (motor skills). Training to use the system appropriately should be implemented, but this should be minimised by good interface design.

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8. Conclusions and Recommendations

This report provides an update of state of the art technology relevant to the SATIN project.
The aim of deliverable was to provide an initial update of state of the art in technology and related research, to add to existing body of work from published literature and relevant other European activities and to provide an integrated overview of scientific and technical progress. This work was collated by all the partners in the WP1 to reflect the diversity of the project.

This report provides a summary of current knowledge in key areas relating to SATIN each of this are sizable research disciplines in their own right.

The key areas reviewed here in version 1 are:

- Haptics technology: advances and innovations in area of the most recently developed haptic interfaces
- Shape modelling: advances in sketching, shape modelling (generation and modification)
- Sound technology: advances in auditory displays, sound technologies
- Visualization technologies
- Human computer interaction: integration of sensory control modalities (visual, auditory, haptic) in multimodal interfaces, human computer interaction and interactive systems design

While a huge volumes of research is available in each area this report has drawn out issues relevant to SATIN.

For each of the sections which discuss technology - haptics, shape modelling, sound and visualization - examples of current state of the art technologies are provided with discussion of future development. Supporting information can be found in the appendices (appendix A: haptic technology data sheets and appendix B: a summary overview of available stereoscopic HMDs). These are presented with proposed recommendations for their application in the SATIN project.

In haptic technologies it is concluded that SATIN required the whole hand type device and that the only feasible solution is that of a local surface patch. Issues related to this include moving bases, adaptive surface patch or 'slice', feeling of sliding, material and number of degrees of freedom and encountered or full contact – sensors on or above the strip.

In the shape modelling sections the technologies which will be considered for their suitability within the SATIN project are advanced global deformation operator and collision detection techniques for real time.

The sound technology section concludes that for real time synthesis for a real and intuitive sound requires the development of faster algorithms.

With regard to visualization technologies there are various display options including HMDs, projection based technologies, holographics, responsive and reactive workbenches. Discussions concerning which is the most suitable method will be made in the next stage of the project.

Human and computer interaction is a research field which impacts on all aspects of design of new technologies. This section considers research that applies to tangible and sound interfaces specifically related to SATIN. This includes the characteristics of tangible and sound interfaces and the application of multimodal interfaces to product design. Interactive system requirements are discussed and the practical considerations in technology design, Human Factors issues and equality and diversity which need to be addressed throughout the project.

These final recommendations will feed into the next stage of the project.

Appendix A. Haptic technology data sheets

This appendix provides information and technical characteristics about some of the main haptic technologies mentioned in Section 3.

MOOG-FCS - www.moog-fcs.com/robotics

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 3DOF

pos. resolution	0.009	mm
stiffness	14.5	N/mm
max. force	12	N
nom. force	12	N

Delta 3DOF

pos. resolution	0.03	mm

stiffness	15	N/mm
max. force	20	N
nom. force	20	N

Delta 6DOF

pos. resolution	0.03	mm
stiffness	15	N/mm
max. force	20	N
nom. force	20	N
nom. torque	200	mNm

HAPTION - www.haption.com

Virtuose 6D35-45

max. force	35	N
nom. force	10	N
max. torque	3	Nm
nom. torque	1	Nm
workspace width	450	mm

Virtuose 3D15-25

max. force	15	N
nom. force	5	N
stiffness	0.8	N/mm
workspace width	250	mm

Virtuose 6D40-40

max. force	100	N
nom. force	30	N
max. torque	10	Nm
nom. torque	3	Nm
workspace width	400	mm

IMMERSION - www.immersion.com

CyberGrasp

max. force	12	N (per finger)

CyberForce

max. force	8.8	N (per finger)
nom. force	6.6	N (per finger)
workspace	12x12	inches x 133 degrees
pos. resolution	0.0024	inches
angle resolution	0.09	degrees

SARCOS - www.sarcos.com

Dextrous arm (large version)

Humanoid robot

SMU - http://engr.smu.edu/me/syslab/PHI/MasterArm.html

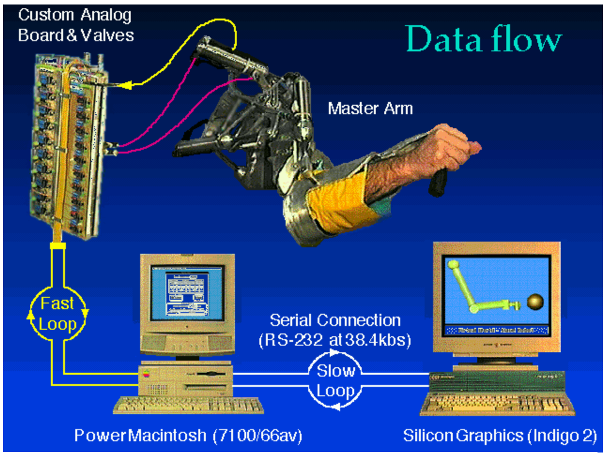
Pneumatic Haptic Interface (PHI)

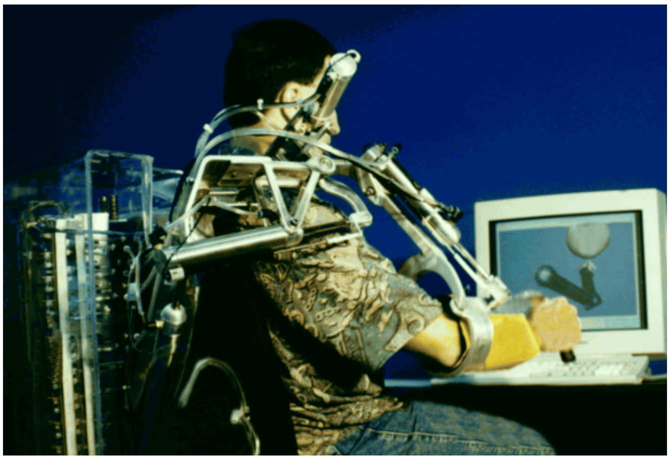
workspace		10	liters
pos. resolution	---	mm	
stiffness		---	N/mm
max. force		---	N
nom. force		---	N
tip inertia		---	kg

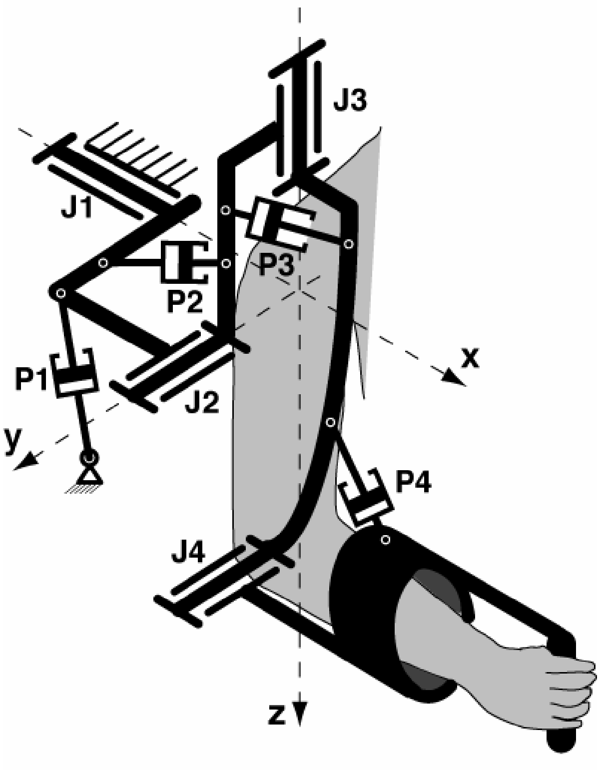
price	---	€

There is a neural network for gravity compensation

The pneumatic force actuation controller is a modified PD (Proportional plus derivative) algorithm that includes specialized schemes to compensate for the aerodynamic effects in the pneumatic circuitry and the cylinders.







Schematic of the mechanical interface

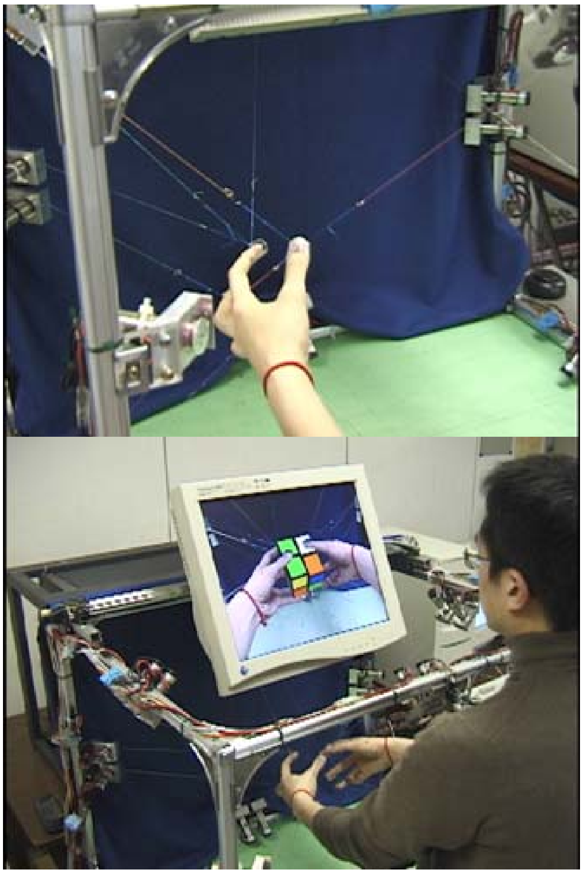
MPB technologies - www.mpb-technologies.ca

Cubic3

max. force	2.5	N
pos. resolution	20	um
force resolution	1.5	mN
workspace	330 x 290 x 220 mm	

SATO-KOIKO group - sklab-www.pi.titech.ac.jp

SpidarG



SENSABLE - www.sensable.com

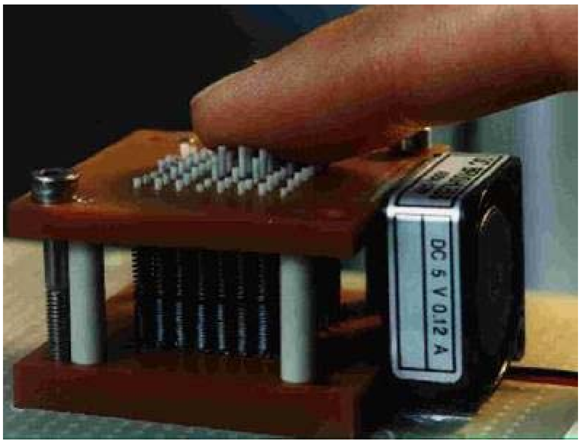
PHANToM Omni

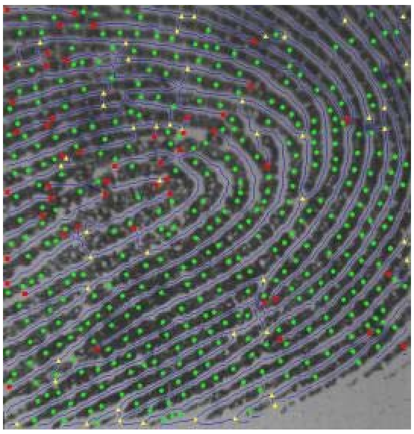
max. force	3.3	N
nom. force	0.88	N
pos. resolution	0.055	mm
stiffness	2	N/mm
workspace	160 x 120 x 70 mm	

PHANToM Desktop

max. force	7.9 N
nom. force	1.75 N
pos. resolution	0.023 mm
stiffness	2 N/mm
workspace	160 x 120 x 120 mm

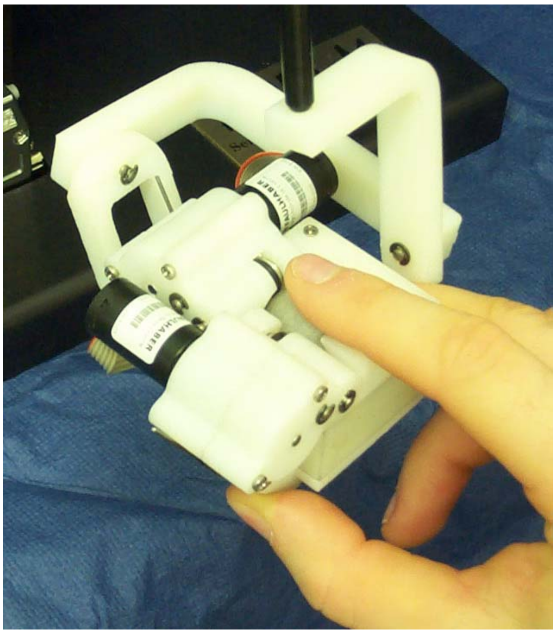
MCGILL University - www.cim.mcgill.ca
Stress





JOHNS HOPKINS University - www.haptics.me.jhu.edu

(add-on slip end effector for the PHANToM)



Appendix B. Overview of available stereoscopic HMDs

This Appendix includes a list of available stereoscopic Head Mounted Display. Sources are the following:

- http://www.elis.ugent.be/ELISgroups/tfcg/microdis
- http://www.stereo3d.com/hmd.htm
- http://www.inrialpes.fr/sed/PRV/CATALOG/hmd.html

	Picture	*Producer*	*Website*	*Product*	*Resolution*	*Color*	*FOV*	*See-Through*	*Weight*	*Price*
1		io-Display Systems	www.i-glasses.com	i-glasses SVGA 3D Pro	800x600 (120Hz)	24-bit	26°diag	no	200g	1.165 EUR
2		nVis	www.nvis.com	nVisor-SX	1280x1024 (60Hz) (LCOS)	24-bit	60°diag	no	1.000g	18.380 EUR
3		nVis	www.nvis.com	nVisor-ST	1280x1024 (60Hz)	24-bit	60°diag	50%	1.000g	26.800 EUR

4		Virtual Research	www.virtualresearch.com	V8	640x480		60°diag	no	1.000g	10.400 EUR
5		Cybermind	www.cybermind.nl	Visette Pro	640x480 (LCD)		71,5°diag	no	840g	2.995 EUR
6		Cybermind	www.cybermind.nl	hir-Res800	800x600		31°diag	no	600g	3.995 EUR (discontinued))
7		Daeyang	www.daeyangenc.com	DH-4400VPD (3D)	800x600 (LCD)		31°diag		155g	discontinued ?
8		Saabtech	www.saabtech.se	AddVisor 150	1280x1024 (LCOS)	24-bit	46°diag	30%	1.000g	76,950 EUR

9		Kaiser-Electro-Optics	www.keo.com	ProView XL35	1024x768		35°diag	no	1.000g	15.000 EUR
10		Kaiser-Electro-Optics	www.keo.com	ProView XL50	1024x768		50°diag	no	1.000g	15.000 EUR
11		5DT	www.5dt.com	HMD 800-40	800x600 (OLED)	24-bit	40°diag	no	600g	7.750 EUR
12		SEOS	www.seos.com	HMD 120/40	1280x1024 (LCOS)	24-bit	153°diag		1.000g	48.000 EUR
13		General Reality	www.genreality.com	CyberEye CE-500S	800x600 (LCD)		30°diag	no		

14		Trivisio	www.trivisio.com	3Scope	800x600 (120Hz) (LCOS)	18-bit	40°diag	no	120g	3.400 EUR
15		Trivisio	www.trivisio.com	52-HMD	800x600 (120Hz) (LCOS)	18-bit	50°diag	25%	200g	prototype
16		Sensics	www.sensics.com	piSight	2400x1720 (60Hz)	24-bit	82-180° diag	no	1000g	N/A