

**Computer-based multi-sensorial environment for  
anatomy teaching :  
The brachial plexus nerves model**

Submitted in partial fulfilment of the requirements for the award of MSc in Engineering and Physical Science in Medicine and the Diploma of the Imperial College

**Imperial College London**  
MSc in Engineering and Physical Science in Medicine

**Samy Tzaprenko**  
**17/09/2008**

---

## **Abstract**

Significant progress has been made in the field of information technologies during the last decade. Computational power today gives the means to handle in real time high resolution 3D models representing biological tissue of interest. At the same time, new means of interfacing with computers such as haptic technology have been developed, adding the sense of touch to the experience of virtual reality. The aim of the project is to develop a cutting edge prototype of computer aided learning system for gross anatomy teaching that combines the sense of touch with three-dimensional vision. The haptic-visual application developed will be based on commercially available and affordable pieces of hardware so that the solution implemented could possibly be scaled-up and used in universities. Particular emphasis will be given to reaping benefits from three-dimensional touch technology and to the development of a user-friendly interface that facilitates the immersion of the student. The result is a three-dimensional haptic enhanced model of the brachial plexus network of nerves that has been assessed by an anatomy teacher and a student. The testers agreed that the developed brachial plexus nerves model is not appropriate for initial learning but is a great supplement to textbook and lectures for revision purpose.

**Keywords :** Haptic rendering, Gross anatomy teaching

## **Acknowledgements**

- I would like to thank Fernando Bello and Harry Brenton for their guidance as well as the rest of the department's team for making possible to work in a relaxed atmosphere
- I would also like to thank Pierre-Frederic Villard for his consistent, fast and valuable help throughout the project.
- My thanks also go to the webmaster of the H3D forum, Marcus for his help and pieces of advice.
- I also give my thanks to Peter Clark who gave highly valuable feedback on the brachial plexus model.

# **Table of Contents**

<b>ABSTRACT .....</b>	<b>2</b>
<b>TABLE OF CONTENTS .....</b>	<b>4</b>
<b>INTRODUCTION.....</b>	<b>5</b>
<b>1) Gross Anatomy teaching .....</b>	<b>5</b>
a) What is Gross Anatomy ? .....	5
b) How Gross Anatomy can be taught ?.....	6
c) Challenges facing Anatomy teaching.....	11
<b>2) Overview of haptic technology .....</b>	<b>14</b>
a) The concept of haptic technology.....	14
b) State of the art haptic systems .....	15
c) Learning by feel.....	17
<b>3) The Brachial Plexus and Nerves of the Upper Limb .....</b>	<b>18</b>
a) Description.....	18
b) Challenge to take up.....	20
<b>MATERIALS &amp; METHODS .....</b>	<b>21</b>
<b>1) Hardware implementation .....</b>	<b>21</b>
a) Advantages of using a Novint Falcon .....	22
b) Drawbacks of using a Novint Falcon.....	22
<b>2) Software Implementation.....</b>	<b>24</b>
a) H3D in a nutshell.....	24
b) Step one : The torso model .....	29
c) Step two : Specification and development of the final application.....	30
<b>RESULTS .....</b>	<b>38</b>
<b>1) Brachial Plexus nerves model : User guide .....</b>	<b>38</b>
<b>2) Brachial Plexus nerves model : setting up.....</b>	<b>45</b>
<b>3) Assessment of our software.....</b>	<b>46</b>
a) timetable.....	46
b) Result of the assessment .....	47
<b>DISCUSSION.....</b>	<b>48</b>
<b>1) Improvement of the brachial plexus nerves model.....</b>	<b>48</b>
<b>2) Usefulness of the brachial plexus nerves model.....</b>	<b>50</b>
<b>REFERENCES .....</b>	<b>52</b>
<b>APPENDIX.....</b>	<b>54</b>

# **Introduction**

## **1) Gross Anatomy teaching**

### **a) What is Gross Anatomy ?**

Anatomy is the science studying the structure of the human body. Anatomy can be subdivided into gross anatomy and microscopic anatomy. Gross anatomy is the study of the body structures that can be seen without using any optical apparatus. Whereas microscopic anatomy deals with structures that cannot be seen by unaided vision [1]. Human beings have since ages shown great curiosity about how they were conceived [Fig.A]. Indeed, researches have shown that in ancient Egypt dissection was carried out as a religious ritual. Through the Renaissance, artists such as Leonardo da Vinci and Michelangelo performed dissection as a way to improve their understanding of human nature [2]. Throughout the 19th century, anatomy became more than just a subject of curiosity as modern surgical techniques required a good understanding of the tissues layout. Nowadays, anatomy is one of the most fundamental disciplines taught in medical school.



**Figure A :** **The Anatomy Lesson of Dr. Nicolaes Tulp.** Rembrandt, 1632. Anatomy lessons were a social event in the 17th century, with students, colleagues and the general public being allowed to attend on payment of an entrance fee.

## **b) How Gross Anatomy can be taught ?**

Anatomy may be studied by bodily regions, such as the chest or the arm, or by determined systems, such as the nervous or the cardiovascular system. Whether Anatomy is taught regionally or systemically, a wide range of methods can be used. Including :

- **Practical lessons using dissection of cadavers by students :**

Cadaver dissection has occupied a fundamental role in the history of medical sciences. As soon as 300 B.C Herophilus performed the first recorded cadaveric dissection [3]. Many academics believe that practical lesson based on dissecting human cadavers should remain the mainstay of anatomy training for students in medicine [4].

Advantages of dissection include, among others :

- Students are provided with the unrivalled occasion to have an insight into the three dimensional structure of the human body. By doing so, they obtain a better comprehension of relative size and position of present structures [5][6].
- Working on a whole-body cadaver encourage the adoption of a systemic approach as the studied part is not separated from the surrounding structures [6][7].
- Students train their manual dexterity and feel the consistency of the tissues [5][6].
- Cadaveric dissection may help students to work through their feelings about the reality of death [5][8].
- Last but not least, dissection offers students a catchy learning experience. Students tend to pay more attention to practical anatomy lessons than to a demonstration where they just have to absorb information passively [9].

However, the necessity for student cadaveric dissection has been challenged during the last decade. Indeed, as it will be explained, dissection of human cadavers raises significant logistic and psychological difficulties.

#### • **Practical lessons using prosection**

A prosection is a cadaveric dissection carried out by a professional in order to demonstrate students specific anatomic structure. In a dissection, medical students learn by doing whereas in a prosection, they learn by watching.

There is a controversy about which place should be attributed to prosection within anatomy courses. Whether prosections are as efficient as dissections in the teaching of anatomy is somewhat controversial in medical education. There are evidences that students that have followed prosection perform as well as students that have taken part to dissection classes at examination [10]. However, some argue that only a part of what is learnt during a dissection is assessed in an examination and that psychological and practical aspect of dissection were not taken into account by the study [11].

The last point is that prosection suffers from the same logistic snags as dissection since cadavers are required. Though less cadavers are needed since a whole class follow the dissection of just one cadaver.

- **Tuition based on radiological imaging**

Medical imaging scans are often used as a way to enhance anatomy lectures and dissection classes [5]. Imaging techniques today such as magnetic resonance or computerised tomography offer very good contrast and fine resolution. Moreover, it is a good point to familiarize students with radiological scans as they will use them after in their work.

- **Didactic teaching**

Lectures and tutorials are often enhanced by the use of anatomical models and skeletons. Teachers also rely on diagrams and photographs found in textbooks to illustrate their course. Lectures are at the core of the teaching of anatomy, however, they must come with other type of approaches where students are much more involved [5]. Research in cognitive sciences has revealed that knowledge obtained through activities that involve the student and arouse its interest is learned more deeply than by rote memorization [12]. Tutorials, for instance are a good way of increasing students participation. Computer based software, as it will be explained, also try to be as much interactive as possible in order to catch student interest.

- **Computer based systems and virtual models**

Progress in computer capacities and data processing allow the design of educationally valuable solution. Enough computing power and mature framework such as OpenGL and H3D are today available. Nowadays, many interactive anatomy teaching packages are on the shelves. Looking for anatomy teaching packages on the medical software website : “RamEx Ars Medica”, dozens of references are listed [13].

Computer based systems often provide students with greater interactivity. Case studies scenarios and mock tests are often included, so that students can work through the material in a ludic way [14].

Some of the recently released software also include three-dimensional virtual scenes making possible to observe the spatial relationship between arrangements and to navigate around the structure looking at tissues from different point of view [15][5]. This is in marked contrast to textbook illustration, diagrams and radiological scans that



are just 2D slices that are sometimes difficult to comprehend and may turn out to lack information needed to correctly assimilate a specific teaching point.

Alongside with being able to navigate freely within the virtual scene, recent computer-based packages may offer other advantages. They often combine conventional two-dimensional scans and diagrams with three dimensional representations of anatomical structures. Displaying 2D representation alongside the corresponding three dimensional model allows the student to learn the critical skill of replacing a 2D slice within its three dimensional context [16]. Indeed, this expertise is essential in interpreting 2D medical scans, especially when intended to pre-surgical treatment planning. Now, let's discuss some of the systems available on the market :

- *Interactive Atlas of Clinical Anatomy* :



**Figure B** : Online advertisement banner promoting the interactive “Atlas of clinical Anatomy”.  
(<http://www.netteranatomy.com/>)

The Interactive Atlas of Clinical Anatomy is a solution developed by Icon Learning Systems [Fig. B]. This package is based on two dimensional illustrations from The Netter Collection of Medical Anatomy which is one of the reference in the area. Icon Learning Systems explains that its solution thanks to its high interactivity is the perfect electronic resource for health education, offering practice and custom tests in a well-integrated format. However, this software does not include real time three-dimensional representations of the anatomical structures. Thus, the interactive “ Atlas of clinical anatomy” is at best a good substitute to conventional textbooks. With a price of about 60 \$, it's the market it seems to target [17].

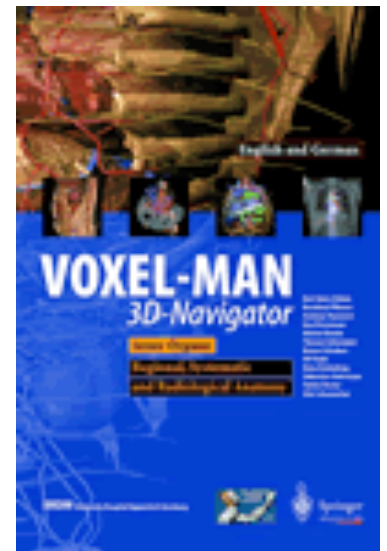
A study about the suitability of such a software has been lead by Etenildo Dantas Cabral & Joanna Barbosa [14]. A class of medical students assessed the use of the software as an educational tool. The result shown that even if three dimensional models were not included, a majority of students though that the computer session helped them

to understand and assimilate the material. It shows that the interactivity allowed by computer based solution confer them a advantages compared to other methods of teaching.

- *Voxel-man Atlases* :

Another solution, “Voxel-man Atlases package” [Fig. C] offers real time three dimensional models of different anatomical structures. This software, developed by the Hamburg university, allows exploration in an unrestrained way as models are not precomputed but displayed in real-time. Voxel-man is one of the best commercial solutions on the shelves today [18]. Main features include :

- Unrestricted choice of viewpoints in a real-time three-dimensional environment with support of endoscopic and stereo viewing.
- Graphical rendering of cutting, allowing simulation of dissection and surgery.
- Simulation of radiobiological imaging: the user chooses a slice and a imaging procedure, then a virtual scan is computed.



**Figure C** : Voxel-man DVD-ROM package.  
(<http://www.voxel-man.de/>)

However, such stunning features have a cost as the full package is sold at \$1,365 which is far more expensive than the Interactive Atlas of clinical Anatomy [19].

To conclude, computer-based systems offer good prospects as they make, by their interactivity, the learning process less monotonous. It is widely accepted that dynamic teaching software are a very good substitute to textebok and plastic models [20][21]. However, the experience offered by available computer-based educative tools are still far from what is experienced during a dissection [6][22][23]. Indeed, dissection is a whole experience involving the sense of touch and going hand in hand with psychological aspects. The next chapter will make clear that even if no suitable substitutes are today available, the interest of dissection and prosection is challenged as these procedures raise important economic issues.

### **c) Challenges facing Anatomy teaching**

Nowadays, the teaching of Anatomy is at a crossroads. Dissection which was a cornerstone of Anatomy teaching is questioned. In addition to the economic problems posed by dissection, other major issues have to be faced in medical university including severe time constraint and stressing lack of anatomists. Let's have a look at the main factors that are inducing changes in how anatomy is taught.

#### **• Is cadaveric dissection noteworthy ?**

The advantages of performing cadaveric dissections and prosections as part of the curricular of medical student were stated in the previous chapter. However, there are manifest logistic and economic problems with these methods. The main issue is the high cost of cadavers which was approximately \$1500 last year in the USA [24]. Indeed, it is difficult to find cadavers suitable for dissection due for instance to illness or obesity [25]. Moreover, cost and availability of laboratory space to store cadavers and cost of preservation procedure must be taken into account. As a further matter, some academics argue that the colour, smell and textures of cadaveric tissues differ from that of living organs, as tissue are altered by preservation [26][27]. As a result, information relative to sense of touch offered by a dissection may be less valuable that one could think at first sight and virtual scenes may offer colour rendering that is closer to what is seen during surgical operations.

Whether pros of cadaveric dissection outweigh cons or not is an highly controversial subject. The arrival of new computer-based teaching methods have been welcomed by some modern anatomists that propose to reduce the time devoted to dissection, as anatomy teaching software may provide, at anytime and cheaply, students with three dimensional views of anatomical structures. Their idea is that dissection should only be kept where practical aspect of dissection play an educational role [28]. For instance, surgeon would still perform dissection as part of their curricular, but this practice would be removed from the core modules that are taught to all undergraduates during their first

year of study. On the contrary, some traditionalist anatomists campaign for cadaveric dissection to be maintained as a foundation of any medical studies.

It remains that realistic enough three-dimensional visual and haptic simulation giving an experience equivalent to a dissection is still not a reality. Further studies must lead to determine whether or not it is a real barrier to substitution of dissection by computer-based models in anatomy course.

- **Problem of curricular changes**

One of the most challenging issues facing Anatomy comes from the increasing amount of knowledge related to new development in fields such as molecular and cellular medicine. Indeed, as it is explained by Harland Winfield Mossman, professor at the University of Wisconsin and president of the American Association of Anatomists (AAA): “ There's so much information that needs to be presented to medical students that something of the ‘old’ needs to be reduced to make space for the ‘new’ ” [29]. Obviously, this increase of the amount of available information goes hand in hand with an increase of the degree of specialisation of the medical students.

Thus a more rational approach of anatomy teaching tends to be followed, students being only taught what they will need as professionals. Classic methods such as dissection are time-consuming and fit less and less easily into the shrinking portion of time devoted to anatomy. Moreover, particular emphasis should be given on efficiency of the teaching methods that are used in order to partially make up for the severe reduction in the time allocated to anatomy.

Anatomy teaching is thus subjected to huge time-constraint that must be considered when thinking about how anatomy should be taught in the upcoming days [30].

- **Shortage of anatomists**

Recent surveys have shown that gross anatomy may soon face shortage of qualified instructors. This issue is extremely serious as 80 percent of anatomy-related chairs that have participated in a survey by the American Association of Anatomists expected difficulty finding gross anatomy teacher in the upcoming five years [29].

This situation may be explained by the tendency observed for at least a couple of decades.

Indeed, many students in anatomy departments have lost interest in gross anatomy and prefer to pursue careers in more recent fields such as cell and molecular biology. Moreover, as it is explained by Robert McCuskey, one of the AAA survey organizers, until now, anatomy have been taught by individuals who did a Ph.D's in the discipline. However, as research is less and less focussed on subject related to gross anatomy, fewer Ph.D.'s are offered in the area [31]. As a result, less and less people are qualified to teach gross anatomy.

Once more, as they are in shortage, available resources to teach gross anatomy must be used in a judicious way and all means of improving the effectiveness of the learning outcomes must be considered.

- **May computer aided learning be the solution ?**

As explained, computer-based systems offer very good prospects, making the learning process more efficient through the good interactivity they provide [12]. Besides, the quality of the last released solution is promising. Even if there is no magic bullet, one can reasonably assert that computer-based systems may help to face the shortage of anatomy instructor and the time constraint faced by gross anatomy teaching [32][33].

However, looking at the commercial solutions on the shelves, one found that they offered limited interaction capabilities with the virtual scene, via standard keyboard and mouse. The immersion of the student in the virtual scene is often very poor. The virtual experience being extremely far from what is seen during a dissection [34]. The idea behind the project was not to try to exactly reproduce what a student goes through during a dissection class as the result would have been unsatisfactory in view of the techniques today at our disposal. But the primary aim was to enhance the user experience, making it more immersive and finally more exciting. With this in mind, the underlying goal of making our prototype assessed by an anatomy teacher and some undergraduate medical students. This project should give a good insight of the prospects given by computer-based teaching systems and will help making the right decisions regarding teaching methods that must be further investigated.

Adding the sense of touch to the model was a salient point in order to enhance the user experience. That is why the next chapter will give a quick overview of the state of the art in the field of touch technology.

## **2) Overview of haptic technology**

### **a) The concept of haptic technology**

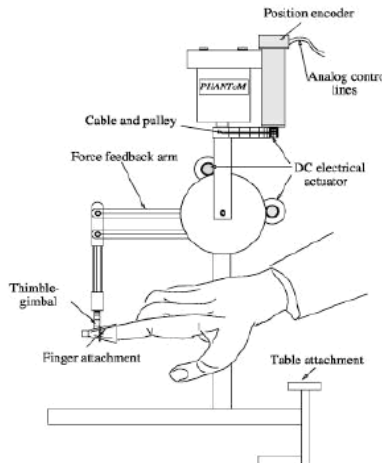
Haptic, from the Greek αφη (Haphe), means “pertaining to the sense of touch”. Haptic technology designates techniques that enable the user to interact with an interface via the sense of touch. In practice, the user feels a force feedback through a dedicated device that depends on the action he did [35]. The bulk of the commercially available haptic devices offer a stylus-based haptic rendering. This means that the user interferes with the virtual scene via a virtual tool or stylus that can be moved around by moving the controller of the device within its scope [36]. This type of interaction may seem quite limited but more elaborate commercially available haptic devices are still not within the bounds of possibility. Nevertheless, when one uses on-the-shelves systems such as the Novint’s Falcon or the SensAble’s Phantom for the first time, the touch experience is really impressive.

The prospects given by this emerging technology are extremely promising. Indeed, touch technology is gaining broad acceptance as a crucial part of virtual reality systems. The realism of training simulator should be greatly improved as a result of these developments [37][38][39]. This may in the upcoming days enable athlete, pilot, surgeon to train them selves as if they were in real conditions.

## b) State of the art haptic systems

Here is a review of some commercially available haptic devices.

### • PHANTOM® (SensAble)



**Figure D** : The PHANTOM Arm  
(adapted from Massie and Salisbury, 1994. ASME)

The PHANTOM haptic device was first introduced in the 1990s. These devices developed by SensAble have been a commercial success as they currently are the most popular haptic interfaces. This device has the look of a robotic arm with a mock surgical instrument fixed at the extremity [40]. The device output encodes the position of its arm which is transmitted to a computer. The software then works out the force that the arm must produce in

order to simulate the virtual environment [Fig. D&E].



**Figure E** : The PHANTOM Omni haptic device.  
(<http://www.sensable.com/haptic-phantom-omni.htm>)



- **Haptic Workstation (Immersion)**



This impressive work station is a fully integrated simulation system, providing right and left-hand force feedback [41]. The user benefits from an immersive virtual experience via head-mounted apparatus. [Fig. F].

**Figure F** : The Haptic Workstation

([http://www.immersion.com/images/right/haptic\\_workstation.jpg](http://www.immersion.com/images/right/haptic_workstation.jpg))



- **Immersive Workbench (SenseGraphics)**

The Immersive Workbench is a haptic system based on a high resolution 3D stereo projector [42]. This hardware is compatible with teaching software such as Voxel-man. It allows trainees to visualise and interact with objects in a virtual work volume.

**Figure G** : Immersive Workbench

([www.SenseGraphics.com](http://www.SenseGraphics.com))



### **c) Learning by feel**

Many recent studies suggest that involving several senses in a learning process tend to improve its effectiveness [43][44][45]. Nowadays, one almost only learn using two of his senses : visual and auditory. Methods that combine multiple senses may lead to increased learning outcomes. Virtual worlds that offer multi-sensorial user experience could have the possibility to act on this lever and create powerful emotional and mental effects on students [46].

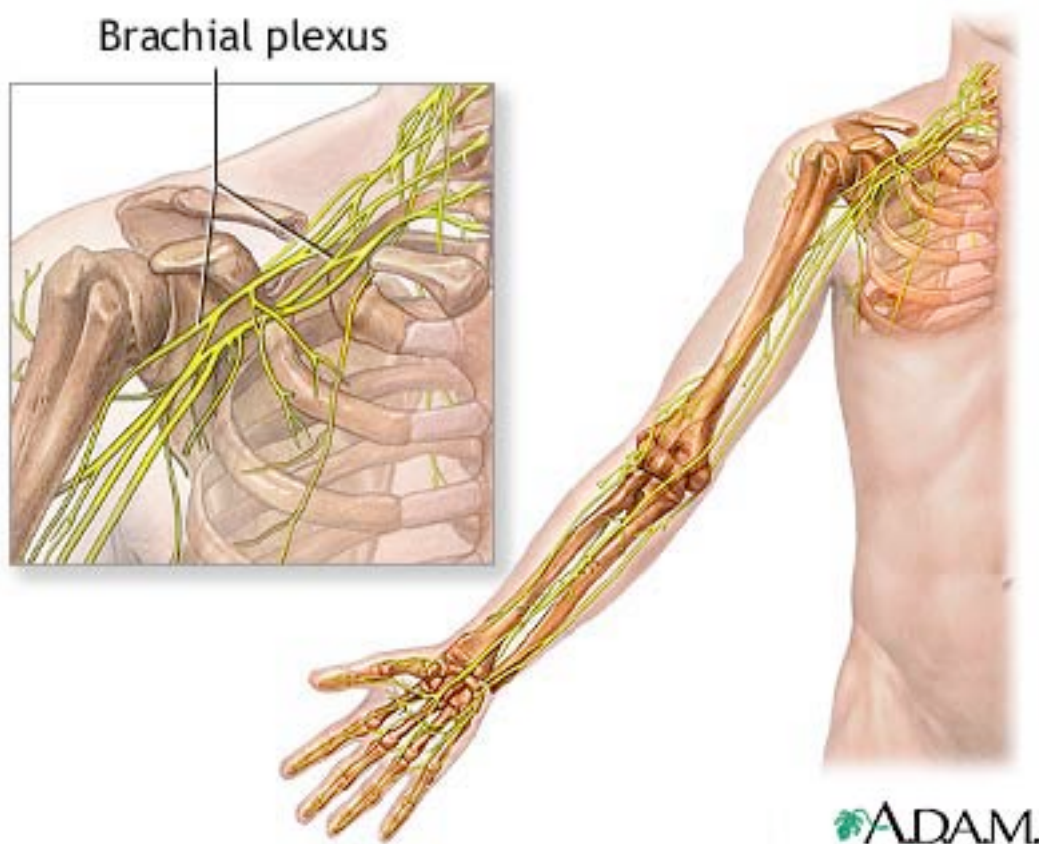
Now that affordable haptic systems are available, there are real opportunities for computer based, haptically-enhanced training simulators. For instance, Novint Technologies has developed a consumer good haptic device called the Falcon that only cost about \$200 which is really cheap compared to the previous solution that were valued at several thousands of US dollars [47]. Thus the « adoption cost » of a switch to haptic enhanced systems can be supported by public education structures. The result will combine the advantages of the existing computer based packages, that include, among others: low running cost, great interactivity, guided lessons without requiring a real mentor to be present , with a highly exciting and immersive user experience.

Having clearly stated the goal of the project, a specific learning scenario still has to be determined. The next chapter will explain why it has been decided to develop a model of the brachial plexus and of the nerves of the upper limb.

### 3) The Brachial Plexus and Nerves of the Upper Limb

#### a) Description

The brachial plexus is an arrangement of nerve fibres that originate from the neck region and is responsible for innervation of almost the entire upper limb [Fig. H]. This group of nerves can be subdivided into 4 distinct regions : the roots, the trunks, the division and the cords [48].



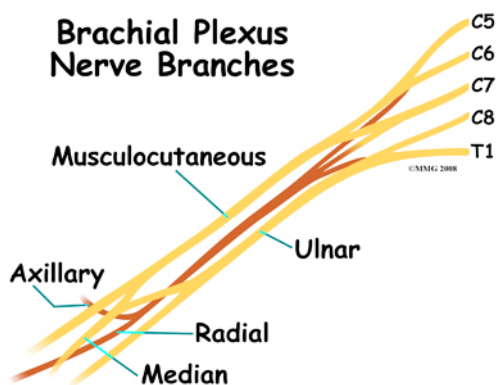
**Figure H** : Illustration of the brachial plexus  
(<http://www.nlm.nih.gov>)

- The **roots** are composed of the C5, C6, C7 and T1 nerves roots. These nerves are the uppermost of the arrangements, they originate from above the fifth cervical vertebra to underneath the first thoracic vertebra.

- These roots regroup to become the three **trunks**. The superior trunk is formed by the C5 and C6 roots, the C7 root turns into the middle trunk and the C8 and T1 roots merge to form the inferior trunk.

- Each trunk then divides into an anterior and a posterior division to form the six **divisions** named after the trunk they are coming from: The anterior division of the upper, middle or lower trunk and the posterior division of the upper, middle or lower trunk.

- At the level of the clavicle the six divisions merge to form the three **CORDS**. The three posterior division of the trunk regroup to become the posterior cord. The lateral cord is formed from the anterior divisions of the upper and middle trunks. The anterior division of the lower trunk becomes the medial cord.



**Figure I** : Brachial Plexus Nerve Branches  
(<http://www.eorthopod.com>)

Then the major peripheral nerves of the upper limb branch from the cords [Fig. I]. The posterior cord divides into the radial and axillary nerves. The musculocutaneous nerve is formed from the lateral cord and the medial cord gives rise to the ulnar nerve.

It is important to note that injuries to the brachial plexus are frequent and may lead to severe functional impairment [49]. That is why the brachial plexus has been thoroughly studied.

## **b) Challenge to take up**

The nerves that compose the brachial plexus are difficult to visualize since they extend over a large area. Students experience difficulties to form a mental image of the arrangement starting from two dimensional illustrations that can be found in textbook. Brian McNamara, consultant neurophysiologist at Cork University Hospital qualifies the brachial plexus of « the spectre that stalks every anatomy student's nightmares » [50].

Because of the difficulties encountered by students with the brachial plexus, this particular region has been chose to be represented in the project.

# MATERIALS & METHODS

## 1) Hardware implementation

The hardware implementation relies on the use of a commercially available haptic device and a stereo projection system coupled with polarizing filters. The force feedback device that has been used is the Falcon haptic device from Novint. This device has been primarily designed for the gaming community. The Falcon haptic device comes with several 3D games where the gamer interacts with the virtual world by moving around a sphere in any direction.

In practice, the Novint Falcon is composed of a handgrip held by three arms coming from the device main body [Fig. H]. These arms have the ability to pull or push the pointing device depending on the input they receive and the force they apply on the grip is updated every thousandths of second. The top of the handgrip displays 4 buttons, that have been used to implement the user interface of the application.



**Figure H** : Picture of the Novint Falcon haptic device. We can see the handgrip in the foreground held by three mobile arms coming from the main body. [47]

3D Touch Workspace 4" x 4" x 4" Force Capabilities > 2 lbs Position Resolution > 400 dpi Quick Disconnect Handle < 1 second change time Communication Interface USB 2.0 Size 9" x 9" x 9" Weight 6 lbs Power 30 watts, 100V-240V, 50Hz-60Hz
--

**Table 1** : Technical specification for the Novint Falcon [47]

### **a) Advantages of using a Novint Falcon**

The main reason for using a Novint Falcon is that it is cheap. As it was said in the introduction, the Novint Falcon has democratized three dimensional touch technology by cutting the price compared to other commercial devices. Although difficult to find when they were first released, the Falcon can now be easily found in large retailer or on online store for about \$200 [47]. The economic affordability of the developed system is a factor that must be thoroughly considered. Using a device as cheap as the falcon we can reasonably imagine to equip a class of gross anatomy with such apparatus.

Besides, the Falcon device has a very robust design. It is less fragile than system such as the Sensable Phantoms as the mobile part is fixed to 3 moving arms. This robustness is a good point for a system installed in an educational environment.

The last point is that the Falcon is handy to use and install, with its USB port the device can be plugged to and then recognized by a PC without further complication. Being easy to maintain is an obvious advantage for a system deployed in colleges.

### **b) Drawbacks of using a Novint Falcon**

The Novint Falcon device is less accurate than more expensive solution such as the PHANTOMS from SensAble. Moreover, the three dimensional touch work space of the Falcon is quite small small: 4"W x 4"H x 4"D for the Novint Falcon, where a

PHANTOM 1.5 exhibits a workspace of 15"W x 10.5"H x 7.5"D [40]. Of course, the displacement of the stylus in the virtual scene that corresponds to a given displacement of the handgrip in the workspace can be tuned. The last point is that the maximal force feedback that the Novint Falcon may apply is lower than what can be achieved with certain more expensive devices. However, the Novint Falcon supports the comparison with its costly competitor. Its specifications [Tab. 1] are sometimes just slightly below what is performed by a far more expensive solution.

To conclude, the disadvantages of using a Novint Falcon are not likely to have a profound effect on success of the developed computer-based teaching system. If the aim of the project were to develop a surgery simulator, factors such as resolution of the haptic rendering and accuracy of the applied force would need to be paid more attention. Developing a virtual reality system intended for anatomy teaching does not bring as demanding constraints. That is why, with its robustness and its low price, the Novint Falcon was a perfect candidate for our system.

## **2) Software Implementation**

The main factors we had to consider to make the right technical decision were the cost, the universality (cross platform, supported hardware), the nature (interpreted, web-based, compiled) and the future prospects of the used technology.

At the beginning, developing the software in Java was considered as it would have conferred it a good cross-platform compatibility and that some java code from a previous project was available. But, following further investigation, it was realized that there was still no Java-compatible haptic rendering framework complete and stable enough to develop the brachial plexus model.

The different possibilities were assessed and it was decided to develop in C++ a software based on the H3D framework.

### **a) H3D in a nutshell**

#### **• Introduction**

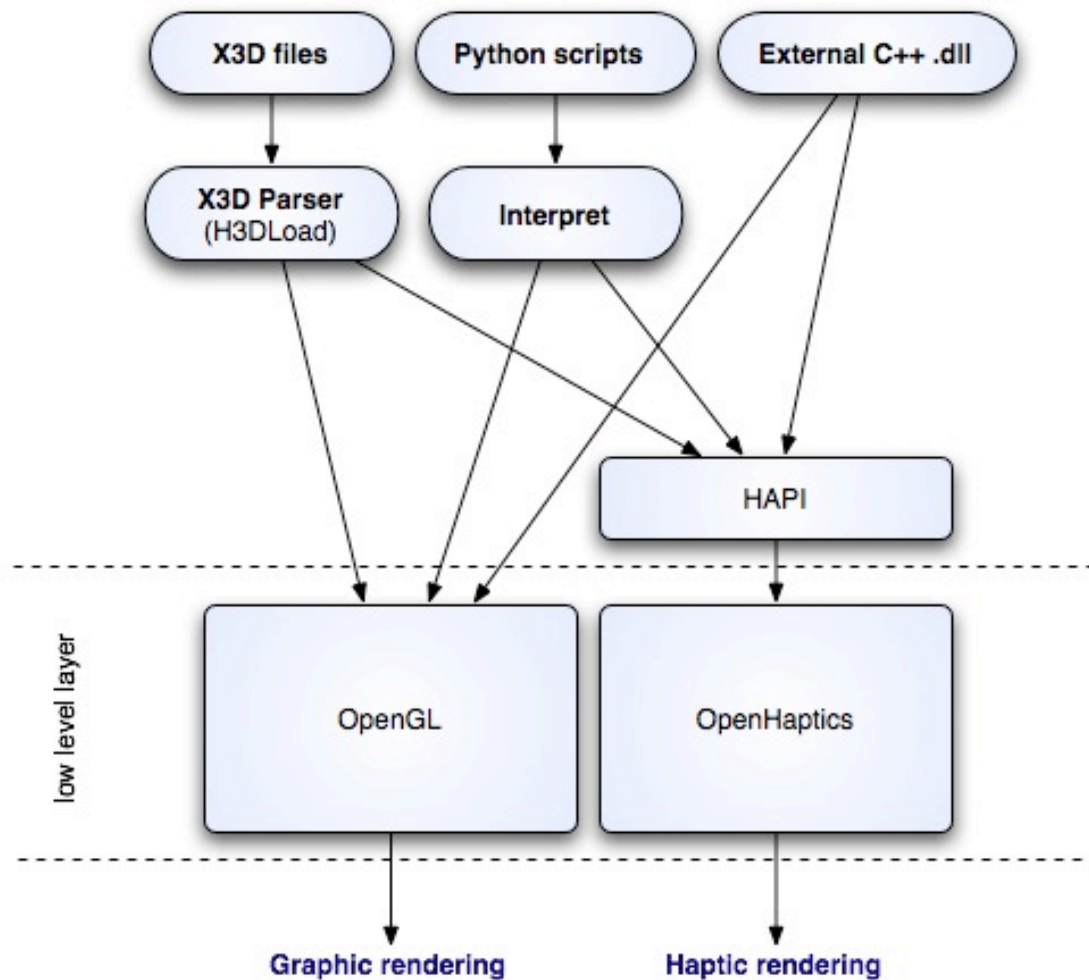
The H3D Framework, developed by Sensegraphics, is a complete set of routines providing all the tools needed to handle and display 3D data easily. H3D supports critical high level features such as haptic rendering and stereo graphics rendering and it offers a scene graph structure which facilitates the definition of virtual scenes. Which means that the scene is broken up into smaller sub-components that all together define the virtual world. What primarily differentiates H3D from the other available frameworks is that it is a scene graph API that performs both graphic and haptic rendering from a single scene description. Indeed, using H3D is like combining a powerful graphic rendering API (such as OpenInventor) and an Haptic library such as Ghost in a way that the haptic rendering corresponds to what is displayed on screen.

H3D is entirely implemented in C++ and relies on OpenGL for graphics rendering and on HAPI for haptics rendering. Moreover, the framework is an open-source and standard-based project developed by a dynamic community placing great emphasis on cross-platform compatibility.



- **General Structure**

H3D heavily relies upon widely adopted industry standards. As we said it, it provides a scene graph representation describing both what is displayed on screen and what haptic behaviour the scene should exhibit.



**Figure 1 :** Classic layout of an application based on H3D

The scene graph representation is based on **X3D** which stands for Extensible 3D file format. This format is itself based on a standard syntax called XML (Extensible Markup Language). The use of the scene graph concept in X3D allows virtual worlds to be easily defined. The X3D file describing the scene of interest is then read by a parser that makes the right **OpenGL** calls to display the scene and the right **OpenHaptics** calls to render the haptic behaviour. Such a parser can be developed from the scratch or derived from H3DLoad, the parser developed by the H3D team.

When complex optimized behaviours that are beyond the spectrum of what can be done by only combining X3D bricks are required, there are two possible solutions. Where performance is not a critical factor, the developer may use the **Python** scripting language, which is an interpreted language. By doing so, the development time may be significantly reduced compared to what is achieved when using only C++. Where speed cannot be trade off, external routines are developed using C++. **External library** (.dll) coded in C++ may have direct access to OpenGL and OpenHaptics layers which provides them with very good execution times. The brachial plexus nerves model that has been developed is based on two external libraries developed in C++.

OpenGL and OpenHaptics are the foundation of the H3D framework. OpenGL (Open Graphics Library) is a cross-platform and cross-language standard that is widely used by application displaying 3D content. OpengGL is an extremely powerful framework that confers to H3D very good performance as all graphics processors support this standard.

- **Haptic rendering**

As offering 3D touch in virtual simulation is still a recent concept, very few scene-graph based APIs offer haptic rendering. Haptic rendering is based on OpenHaptics which is an API developed by SensAble sitting at the same level as OpenGL, but dealing with the haptic rendering. HAPI is an intermediate level that has been developed by the H3D team. It provides us with higher level function that, amongst others, enables OpenHaptics to render haptic information described by scene-graph data.

H3D today supports most of the commercially available haptic devices, which includes Phantom devices developed by SensAble Technologies Inc, Force dimension devices and the Novint Falcon devices on which our solution is based on.

- **Stereoscopic display**

H3D provides an embedded support of stereo graphics rendering. The stereoscopic display just has to be activated and the space between the two displayed scenes tuned in

order to obtain a stunning three dimensional stereoscopic display. The immersion of the user is greatly enhanced by this feature.

- **Concept of Field and Node**

Programming using H3D is based on the concept of Field and Node. These concepts are inherited from X3D where they are used in the scene-graph division.

**Fields** are the most fundamental entities in H3D. In a nutshell, a field is a data container that knows how to update the values it contains. Values stored in a field may depend on a value contained in another field, in which case a **route** is set up between the concerned fields. When the value of a field is modified, an event is generated to inform the fields routed to it that the value has changed. The idea is that fields that depend on the modified field know that the values they contain are not up to date. Thus, if (and only if) the value of an updated field is requested, the field will work out the updated value and return it. This kind of behaviour is called lazy-evaluation: the value of the field is derived only if needed. In some occurrences, and it is the case for some of the fields contained by the control node used in the developed model, values must be updated at in real-time. For instance, when events are generated by a pressed button and that one wants some values to be correct at this time, lazy-evaluation is not satisfactory. That is why H3D enables to define fields that update the data they contain automatically, without waiting for an incoming request.

In practice, fields are C++ classes inheriting from a common H3D class : SField. The H3D package already defines a large number of classic fields. For instance SFBool is a Field that contains a Single Boolean and MFBool is a Field that contain several Boolean. Our model uses several dozens of fields predefined by H3D including : SFInt32, SFVect3f, SFColor, SFRotation, SFFloat. For some specific tasks, customized fields have to be implemented [Appendix] . For example, we may define a field that returns a color as output value but that takes a boolean as input value. This kind of customized fields that take some type of data as input value and work out an output value of a given type are heavily used when programming with H3D. Last but not least, in Sfield, the mother class of all fields, is defined functions such as update() and render(). These functions can be redefined or customized so that fields follow a given behaviour.

**Nodes** are entities that encapsulate fields. The field network of the application is subdivided into several nodes. Fields that are owned by the same node can share common data that are stored into the node and may also access to each other if required. From a technical point of view, a node is a C++ class inheriting from the Node class implemented in the H3D framework and the fields it contains are object that are part of its attributes. When nodes are instantiated by the X3D parser, its fields are also instantiated by the constructor of the node. As it is explained in the H3D API Manual, « In theory an entire application could be written in H3D using only the field network ». However, as the application is getting elaborate, the field network becomes rapidly out of control. Enclosing its fields in distinct nodes is a good way to ensure that the application is well designed.

The brachial plexus model follows design guidelines given by the H3D team. Our simulation is composed of an X3D file and of two external libraries developed in C++. These .dll corresponds to two customized nodes: the « Control node » and the « Individual node » that will be described afterwards.

#### • **H3D snags**

As written, H3D is an extremely powerful framework offering impressive features. However it suffers from some snags, including:

- There is very little documentation about H3D. There is an official H3D API manual that can be downloaded on the H3D website dealing with H3D installation and giving some basic information about how application should be designed when using H3D. A wiki is also available from the website, but it gives access to very little material. Some very useful simple codes are hopefully provided in the package. Nevertheless, getting started with H3D remains quite demanding.
- Even if once understood the H3D design turns out to be extremely well thought, the structural division between field and node is difficult to apprehend for developers that are not used to this concept.
- Installing H3D is very laborious. A significant part of the time worked on the project was spent trying to resolve incompatibility between libraries.

- H3D is not web-based and does not support any communication protocol. Developing a client/server application, to enable team-work on a same model, is still possible but the network part as to be entirely implemented.

## **b) Step one : The torso model**

Before implementing the brachial plexus model, work has been done on a simpler 3D scene. This first X3D model, enhanced by a customized node, represents a human torso and a liver which is not at the right scale. During this first stage, the idea was to get familiarized with the development tools and the H3D frameworks. The goal was to implement a basic user interface, listening input from mouse and keyboard and to develop features such as labelling and highlighting on touch.

The first step was to develop a dll library and to load it into an X3D file. The customised node has been derived from the H3D node CoordinateDeformer. CoordinateDeformer node is a node that is placed within a DeformableShape node. It has a virtual function called deformpoint that gives access to the coordinate of the considered shape. The interest of this function is that all the information needed to handle the haptic device interaction with a shape is at hand.

Using this available information, the node has been implemented so that shapes are highlighted when touched. Moreover, MouseSensor and KeySensor nodes from H3D package have been routed to proper fields so that information of interest is collected. To conclude, a simple model based on an X3D file enhanced by a customized node has been developed. It displays some of the required behaviour, such as highlighting and labelling on touch [Fig. J].

However, on many points, the result was not satisfactory. First, the collision detection of the haptic device stylus with the three dimensional shapes was not fast enough, causing the stylus to go through shapes supposedly stiff if the displacement was too brisk. Moreover, the technique used to display the labels was not acceptable. What was done was to load all the labels in the 3D scene with a maximal transparency and then to switch them on whether a shape was touched or not. Thus, if the user changed the initial orientation by rotating around the model then the labels were not displayed in the good plane. However, the main goal to get familiarized with H3D was reached.



**Figure J** : Screenshots of the torso model. Upper screenshots have been snapped just before contact. Lower screenshot have been taken during contact : the touched element is highlighted and a label is displayed

### c) Step two : Specification and development of the final application

#### • Specifications

The project specification have been given by a Ph.D student Harry Brenton, working on multiple external representations for anatomy teaching. They have been refined as the development was going on and that new ideas were suggested.

- The application must display the nerves, muscles and bones in a real time three dimensional scene supporting haptic rendering and stereoscopic graphical rendering.

- The user interface must support 3 modes of use, as indicated in the following table [Tab. 2].

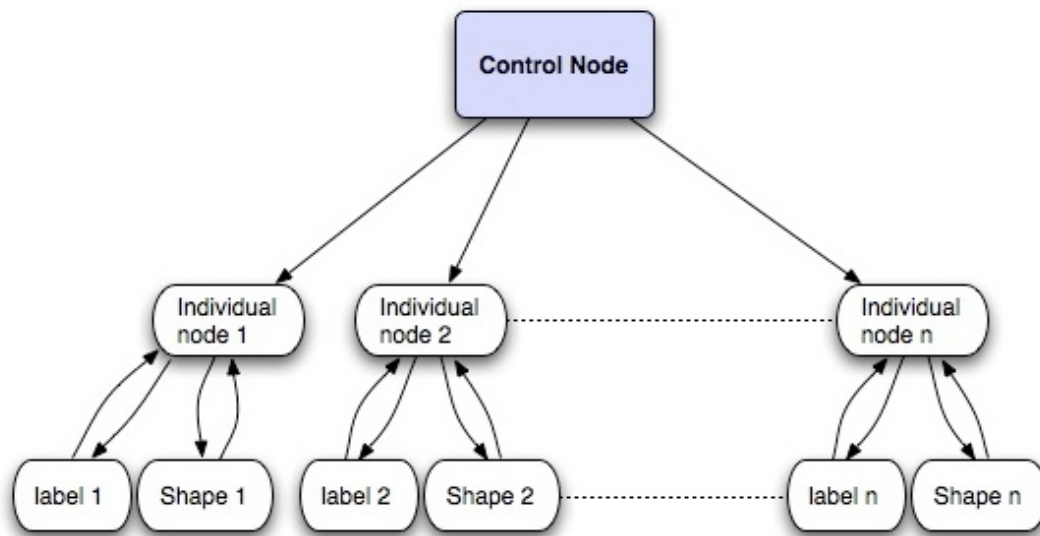
Mode	Function	Details
<b>Stripping</b>	Stepwise addition and subtraction of layers. two keys are put in play, one to add and one to remove components.	<p>Nerves are ‘built up’ bit by bit. According to the following sequence :</p> <p><b>1. nerves:</b>            C5 root, C6 root, C7 root, C8 root, T1 root,            Superior trunk, middle trunk, inferior trunk            Anterior division superior trunk,            Anterior division middle trunk,            Anterior division inferior trunk,            Posterior division inferior trunk            Posterior division middle trunk            Posterior division superior trunk            Lateral cord, posterior cord, medial cord,            Musculocutaneous nerve, axillary nerve, radial nerve,            median nerve, ulnar nerve.</p> <p><b>2. Bones</b></p> <p><b>3. Muscles:</b>            Musculocutaneous innervates            Axillary innervates            Radial innervates            Ulnar innervates            Median_innervates</p> <p><b>4. Skin</b></p>
<b>Navigating</b>	Translate and rotate the model. Zoom in and Zoom out.	
<b>Preset Zoom</b>	The view zooms on different region of interest.	A two dimensional bitmap view that indicates the position of the zoomed region within the whole model should be displayed.

**Table 2** : The three modes of use

- Muscle, nerves and bones must display different level of stiffness
- Nerves and muscles should be highlighted when touched by the stylus
- Nerves and muscles should also be labelled on touch
- The user interface must be as much user-friendly as possible, only involving the displacement of the haptic device handgrip and the buttons displayed on its top.

### • Structure of the brachial plexus model

In the developed application, nodes are organised under a pyramidal layout [Fig. K]. At the top of the structure is sitting the control node, giving information to each individual node, such as for instance the current level of stripping. Each individual node works out information received from the control node and sends suitable signals to the component it is associated with. In the next chapter, the structure of the Control and Individual nodes will be given.



**Figure K** : pyramidal layout of the nodes in the nerves simulation

### • The control node :

The control node plays a central role in the developed model, it aims at :

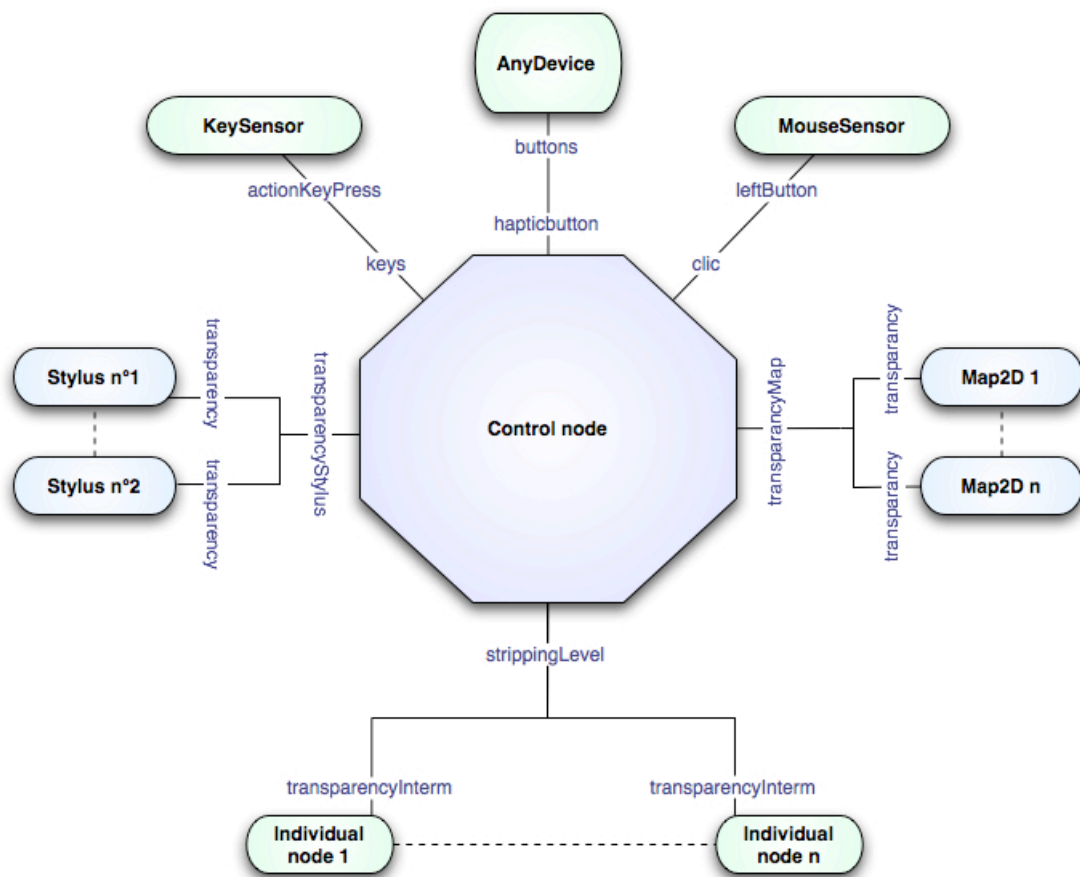
- Keeping data referring to the whole system that are shared by all the other nodes. This kind of information for instance includes the number of shapes composing the model, the mode currently used, how many layers have been removed by the stripping function or the color taken by components when they are touched.
- Implementing the user interface by listening the input received from the buttons of the haptic device and carrying out suitable treatment of this information.

There is no route from the individual nodes to the control node so that extra shape can be added by just modifying the arguments given to the control node during its



initialisation, without recompiling the library. This is a salient point as it makes the control node reusable in any other model given that some minor modifications have been made to the X3D file of interest.

From a technical point of view, the control node is a class that inherits from X3DchildNode which is a H3D node sitting just on top of the Node class. X3DchildNode is an abstract node from which customized node can be built.



**Figure L** : Structure of the Control node

The figure L gives an overview of the structure of the Control node. Green boxes are nodes that are routed to the control node which is represented in blue at the center of the diagram. Labels on the link correspond to the name of the fields that are linked by the route. Knowing that fields belong to the node they are placed just next to in the diagram. As explained, « individual nodes », that corresponds to the different components of the scene, are listening the control node through a common interface :

the `strippingLevel` field. The Control node does not listen at individual nodes as it will require to instantiate a field for each individual node in the arguments of the control node and thus would have required to recompile the Control node for each added component.

Let's describe the main fields that are used by the control node [\[Appendix\]](#) :

- **keys**, **click** and **hapticbutton** are fields that process input information respectively coming from keyboard, mouse and haptic device. This information is given by sensor nodes (`KeySensor`, `MouseSensor` and `AnyDevice`) that are implemented in H3D framework. Here is a scenario that explains what is happening when the mode button is pressed. While the user is exerting pressure on the button, events are generated at each main loop iteration by the `AnyDevice` node. The value of the field « buttons » of this node, which is of `SFInt` type, takes a value that depends on the pressed button. The bit number `x` indicates the state of the buttons number `x`, a value of 1 corresponds to a pressed button. The value of the field « buttons » is collected by the « `hapticbutton` » field which is owned by the control node. The control node changes the active mode when the first event of this type is received and then ignore the next events of the series, waiting for the series to end before taking again into account the events of same type [\[Fig L\]](#).

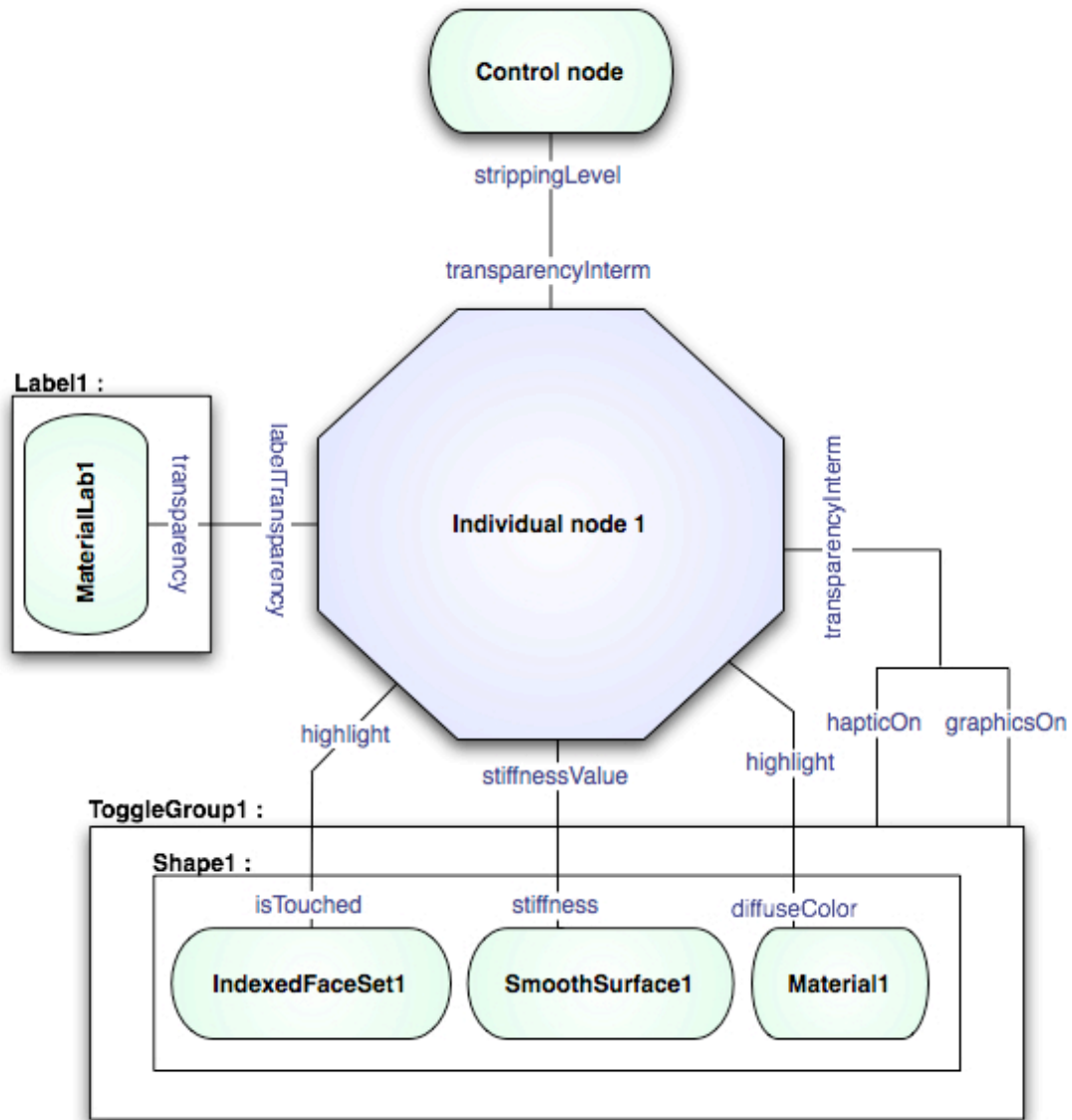
- **transparencyMap** is a field that derives from `SFFloat`. It enables the control node to controls the degree of transparency of the two-dimensional map displayed when a preset zoom is activated. The value of these fields is computed so that only the right map is displayed when using preset zooms.

- **transparencyStylus** is also a field that derives from `SFFloat`. It allows the control node to display the stylus that corresponds to the active mode. When an event generated by the node `AnyDevice` is received by the control node and that this event corresponds to the « mode button », the control node updates the value of a static variable that indicates which mode is currently active and the `transparencyStylus` value in order to display the correct stylus.

- **strippingLevel** is a field of type SFInt32. It's value indicates the current level of stripping. This value is read by the individual nodes. Each individual node knows from which strippingLevel value the component it manages must be masked.

- **The individual nodes :**

An individual node aims at storing data relative to a given component of the scene. For instance at which position the shape is removed during stripping, the stiffness of the shape when stylus is in contact and parameters of this kind. An individual node is instantiated and associated with each element of the model. Besides data storage, the individual node controls parameters that define the component it is in charge of.



**Figure M** : Schema of Individual node input/output

Let's describe the main fields that are used by an individual node :

- **transparencyInterm** is a customized field whose update function takes as input a SFInt32 provided by the control node as explained previously and that works out a boolean that is true if the component should be displayed and false if it should not. This boolean is sent to the field hapticOn and graphicsOn contained by a ToggleGroup node that itself contains the shape node of interest. The point is that every component is

encapsulated within a ToggleGroup node which controls whether its haptic and graphical rendering must be carried out or not [Fig. M].

- **highlight** is a customized node whose update function takes as input a boolean and that derives a color object depending on some parameters. The input boolean is provided by the IndexedFaceSet node associated with the component. This IndexedFaceSet node stores the raw three-dimensional data defining the shape of the component. IndexedFaceSet is also involved in the collision detection of the stylus with the element. The SFBool field «isTouched» is true when the stylus touches the component. Depending on the value of the boolean, the correct color is sent to the field diffuseColor of the Material node, defining the color of the touched structure [Fig. M].

- **StiffnessValue** is a SFFloat field that is routed to the field stiffness of the SmoothSurface Node. The SmoothSurface node handles the haptic behavior of the shape it is associated with. The StiffnessValue field thus enables the individual node to access to the component stiffness.

# RESULTS

## 1) Brachial Plexus nerves model : User guide

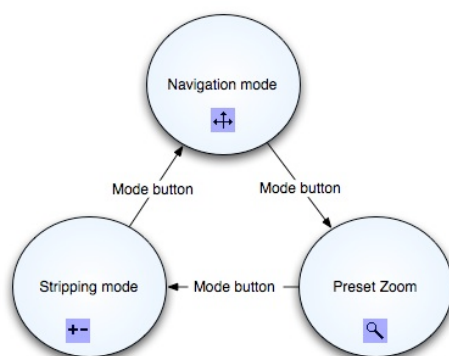
The following user guide has been distributed to the tester (the gross anatomy teacher and the student) prior to their assessment of the brachial plexus nerves model.



**Figure N** : Controller of the Falcon Novint haptic device

The Falcon Novint controller exhibits 4 buttons. Here is a picture of the interface :


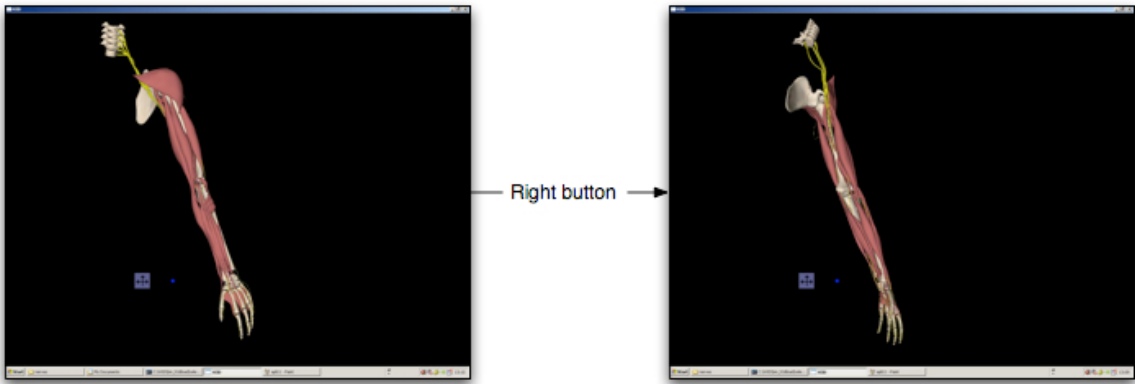
The **Mode button** allows the user to switch between the different modes of use that have been implemented. These modes are : « Navigation mode », « Preset zoom mode » and « Stripping mode ». The mode that is currently active is pointed out by a little flag that follows the stylus. The sequence as the mode button is pressed is indicated by the following diagram :

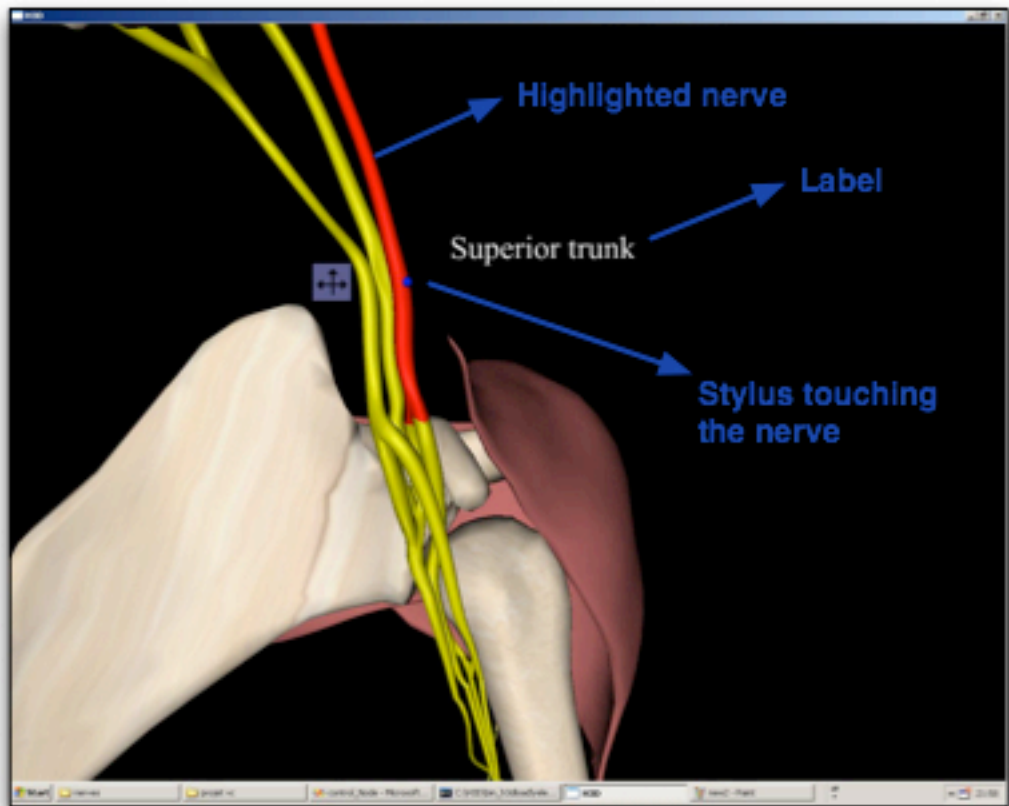
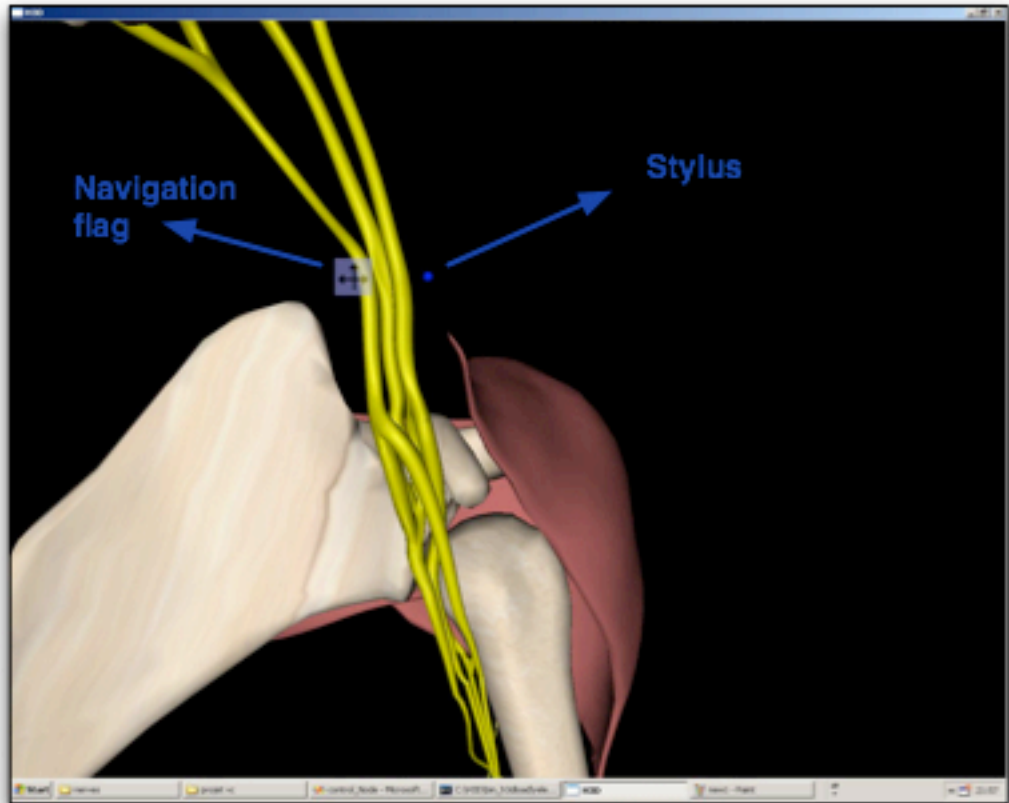


**Figure O** : Sequence of successive activated mode

The action triggered by the three other buttons depends on which mode is currently active. The following tables summarize which action is triggered according to the the current active mode and the pressed button.

• **Navigation mode :**


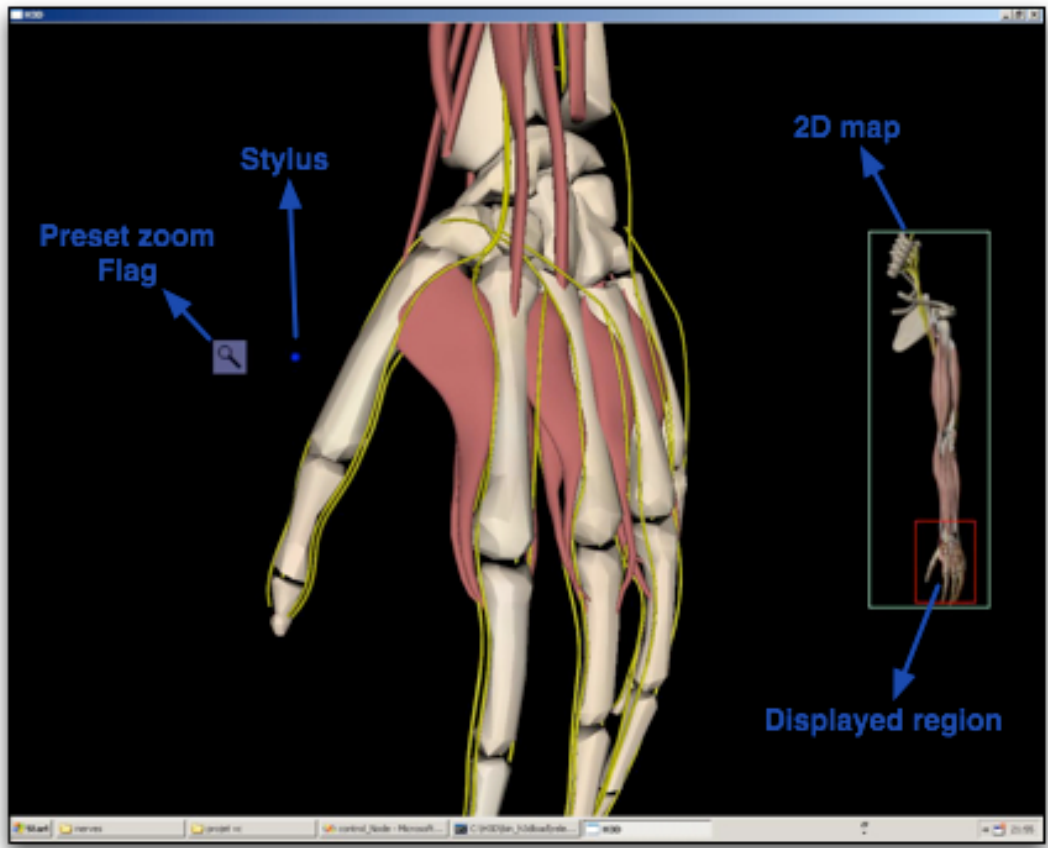
<b>Displayed flag</b>	
<b>Main button</b>	The user can zoom back and forth and make translation of the model by intuitively grabbing it and moving it around
<b>Left button</b>	When this button is pressed, a clockwise rotation along the main axis is triggered.
<b>Right button</b>	When this button is pressed, an anti clockwise rotation along the main axis is triggered.
<b>Illustrations</b>	<div style="text-align: center;">  </div> <p>Prior the screenshots to be snapped , the user zoomed out, grabbing the model and moving it backward. Then, between the two snapshot the viewpoint is rotated around the model using the right button</p>

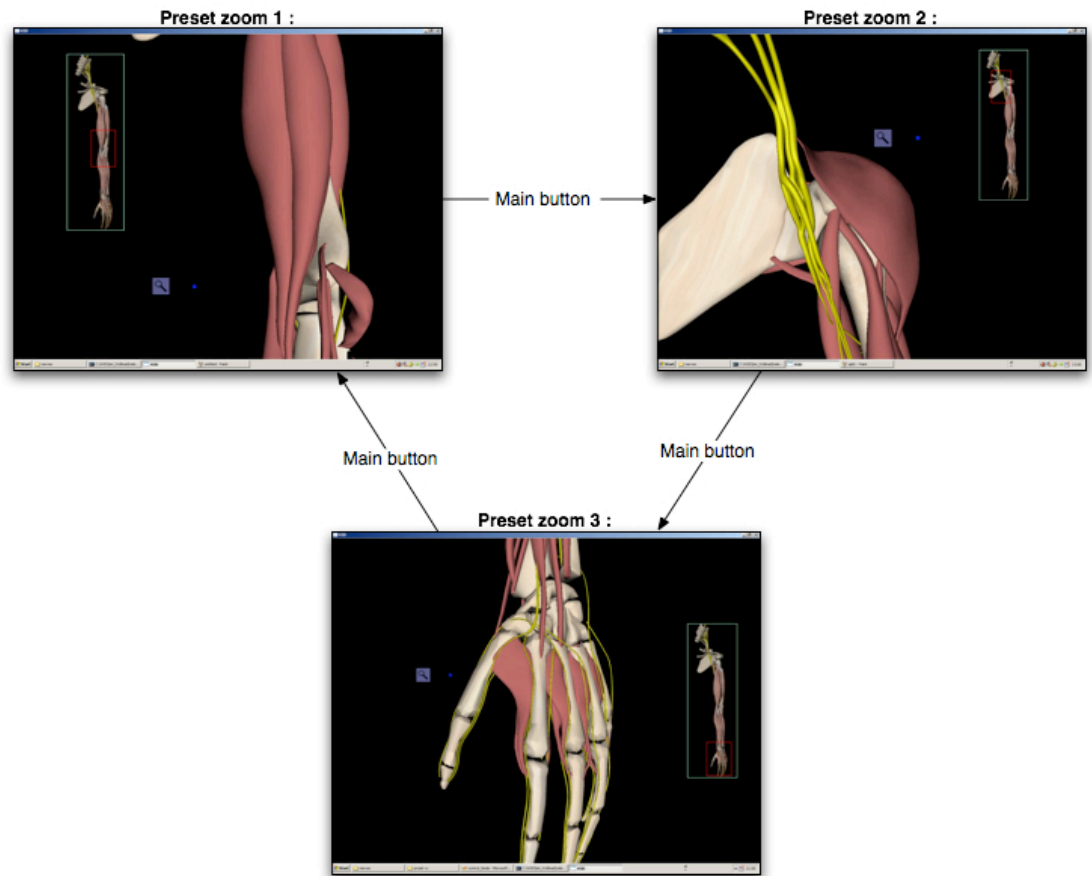


When the stylus touches a component it highlights it and a descriptive label is displayed. The upper screenshot is snapped before contact is made and the other one just afterward.





• Preset zoom mode :

<b>Displayed flag</b>	
<b>Main button</b>	The user passes from one preset zoom to another by pressing the main button. For each zoom, the corresponding two dimensional picture is displayed
<b>Left button</b>	Unused
<b>Right button</b>	Unused
<b>Illustrations</b>	 <p>This screenshot has been snapped as the preset zoom 3 is active. On the right, a 2D map of the whole model is displayed in a green box. A red box drawn on the map indicates which region is put on view</p>



These screenshots show the sequence followed by displayed preset zooms as the user is pressing the main button

• Stripping mode :

<b>Displayed flag</b>	
<b>Main button</b>	Unused
<b>Left button</b>	Stepwise addition of layers
<b>Right button</b>	Stepwise suppression of layers
<b>Illustration</b>	 <p>In these screenshots, the user is stripping out the model, removing components one by</p>

one by using the left button.

Nerves are 'built up' bit by bit according to the following sequence :

**1. nerves:**

C5 root, C6 root, C7 root, C8 root, T1 root,

Superior trunk, middle trunk, inferior trunk

Anterior division superior trunk,

Anterior division middle trunk,

Anterior division inferior trunk,

Posterior division inferior trunk

Posterior division middle trunk

Posterior division superior trunk

Lateral cord, posterior cord, medial cord,

Musculocutaneous nerve, axillary nerve, radial nerve, median nerve, ulnar nerve.

**Note**

**2. Bones**

**3. Muscles:**

Musculocutaneous innervates

Axillary innervates

Radial innervates

Ulnar innervates

Median\_innervates

**4. Skin**

## 2) Brachial Plexus nerves model : setting up

Once the application developed, suitable value has to be given to the initialisation parameters. These parameters correspond to the values taken by the fields during the initialisation. These value are stored in the X3D file and given to the nodes when they are instantiated. For instance, the different colours that were used, the relative stiffness exhibited by the different biological tissues, the coordinate of the viewpoint at launch and viewpoint parameters corresponding to the preset zooms had to be tuned. In this table are summarized the values that have been set up.

Parameter	Range of possible value	Used value	note
Color of nerves	(0..1, 0..1, 0..1)	(0.8, 0.8, 0.0)	Yellow expressed in the RGB color system
Color of Muscle	/	(0.72, 0.36, 0.36)	/
Color of nerves when highlighted	/	(1.0, 0.0, 0.0)	/
Color of muscle when highlighted	/	(1.0, 0.0, 0.0)	/
Color of labels	/	(1, 1, 1)	/
Stiffness of nerve	0..1	0.7	
Stiffness of muscle	0..1	0.8	
Stiffness of bone	0..1	1.0	
Number of components	0..a	29	
Initial level of stripping	0..a	29	
Number of preset zooms	1..b	3	
Label offset	(0..x, 0..y, 0..z)	(0.03, 0.0, 0.1)	(along x axis, along y axis, along z axis)
Label font size	0..1	0.02	
2D Map size	(0..x, 0..y)	(0.102, 0.315)	

**Table 3** : parameters of the brachial plexus nerves model

### 3) Assessment of our software

#### a) timetable

Schedule of the testing session of the brachial plexus teacher made by Harry Brenton :

Time	Event	Location	Action
14.00 9th Sept			Set up & test hardware and software
08.00 10th Sept	HB arrives		
09.00	ST arrives		Test software & haptics
10.00	PC arrives		Briefing with HB
10.20	Participants arrive		Briefing with HB and PC Read info sheet, sign consent form
10.25	Start local recording	Demo room	
10.25	Start remote recording	1035	
10.30	Session 1 starts	Demo room	
11.00	Session 1 ends		
11.05	Participant group interview	Demo room	HB or another
11.35	Download files		

#### Contacts

HB Harry Brenton Researcher  
ST Samy Tzaprenko Researcher  
FB Fernando Bello Researcher  
PC Peter Clark Brachial plexus teacher

## b) Result of the assessment

The models has been tested and rated by an anatomy teacher and a student after they followed a session of about 30 minutes. The whole training session has been recorded by cameras filming how they were dealing with the haptic device. A screen recorder has also been installed on the computer to keep record of what happened on screen. The tables below summarize the rating testers gave on several facet of the brachial nerves model. The choice in red is the one given by the professor.

**Table 4** : Rating of technology :

	Very good	Good	Adequate	Bad	Very Bad
Overall usability		1	1		
Overall quality	1	1			
Haptic device		1	1		
Stereo display	1	1			
3D Model	1		1		

**Table 5** : Rating of the usefulness of this technology for learning :

	Very good	Good	Adequate	Bad	Very Bad
To supplement lectures	1	1			
To supplement textbooks	1	1			
To supplement small group tutorials		1	1		
For initial learning			1	1	
For revision	2				

## **DISCUSSION**

It has been regretted that just one teacher and one student assessed the developed model. With much more testers, the significance of the obtained ratings would have been greatly improved. However, ratings are not the only outcome of the assessment. The anatomy teacher has been interviewed at the end of the teaching session and many crucial issues have been raised during the discussion.

### **1) Improvement of the brachial plexus nerves model**

#### **- The user interface and the haptic device**

Overall, the feedback from the testers about the user interface was quite good [Tab. 4]. What they found is that at the beginning it was a little difficult to get familiarized with the haptic device. Neither Peter Clark, the anatomy teacher nor the student used this kind of controllers beforehand. After a few minutes they found it easier to navigate around the model and to use the different features such as stripping and preset zoom. It can be noticed that the student got used to it more quickly than the teacher. As explained by Peter Clark : « I think initially [the user interface] is a bit frustrating because you press the wrong buttons, but again I think the gaming generation will do that within seconds ». This is not surprising that young people, who grew surrounded by computers, feel more familiar with this kind of technology. This generational factor has thus to be taken into account when assessing the friendliness of the user interface. Peter Clark also put forward the idea of developing elementary tutorials aiming at accustoming users to how the model works. For instance, making the user dragging a shape back and forth to get used to the navigation mode. In short, the testers initially experience some difficulties with the user interface as they were not familiar with it. Though, as they were using it they quickly felt more and more at ease.

#### **- Stylus stuck into a bit**

The stylus gets sometimes stuck into nerves or muscles. In such case the user may make a brisk movement to set the stylus free or use stripping to remove the element within which the stylus is stuck. The last solution is to switch to preset zoom mode and



to restart the viewpoint and the stylus position by choosing a zoom. What we could do to avoid the stylus to go through stiff surfaces is to increase the haptic frame rate. This could be done by using a more powerful computer or by optimising the haptic rendering algorithm which seems quite difficult to realise. Another solution could be to use 3D models with an higher resolution and to make sure that there is not opening within the shape.

#### **- Problem with selecting thin nerves**

It was noticed, during the assessment that some very thin nerves were difficult to touch with the stylus. To overcome this problem the dimension of the stylus could be increased. However, increasing the stylus dimension goes hand in hand with a loss in accuracy. The solution could be to display a magnetic haptic rendering for small and thin structures. There is a node, « MagneticSurface », developed by the H3D team that allows to implement such a magnetic haptic rendering. The distance from the surface within which attractive forces are generated depends on the value of the « snapDistance » field. The « MagneticSurface » node has not been used in the brachial plexus model because it was not compatible with the haptic rendering algorithm used : « GodObjectRenderer ». Only « OpenHapticsRendering » enables to use the « MagneticSurface » node. Recompiling H3D with the OpenHapticsRendering algorithm as standard haptic renderer and replacing the « SmoothSurface » node by a « MagneticSurface » should without, much effort, significantly enhance the user experience.

#### **- Highlighting and labeling on touch**

In the tested version of the brachial plexus model, when the user highlights a specific nerve by touching it, the name of the nerve is displayed next to the anatomical structure. But when it is a muscle that is touched by the stylus, the displayed text indicates by which nerve the muscle is innervated. Peter Clark questioned the logic behind this behaviour. He thought that it would make more sense to display the name of the touched muscle next to the contact point and supplementally to indicate by which nerve it is innervated somewhere else on screen.

## **2) Usefulness of the brachial plexus nerves model**

### **- Usefulness of the stereoscopic projection**

At first, testers said they regretted the obscurity required for the projection and the need for stereoscopic glasses to be wear. This conditions may complicate the use of other material such as a textbook while using the brachial plexus model. However, the anatomy teacher and the student both agreed that the stereoscopic projection was really impressive [Tab. 4]. They explained that the user experience was far more immersive than with a classic projection. Moreover, they said that such a stereoscopic view should greatly help the students to visualize the anatomical structures in three dimensions which is a salient point in the understanding of the brachial plexus system.

### **- Usefulness of the haptic rendering**

When asked how touch feedback enhanced the brachial plexus model, the anatomy teacher replied that according to him the advantages of interfacing with the model via the haptic device were not that much. He explained that, as far as he is concerned, the model would certainly be easier to handle with a standard mouse to which he is more accustomed. However, to quote the teacher own words: « It maybe, that you know the gaming generation would find it much more useful than I would ». To conclude, further investigation must be carried out in order to evaluate the interest of haptic feedback in anatomy teaching. A larger sample of testers should assesses the developed software, and the generational facor must be taken into consideration when examining the resulting data.

### **- Initial learning or revision ?**

The teacher and the student both agreed that the brachial plexus nerves model that they tested is not appropriate for initial learning [Tab. 5]. Peter Clark explained that in order to be suitable for a first exposure to the brachial plexus, the model should incorporate introductory material. This starting material should include basic explications and makes clear why this particular anatomical structure is important. Thus adding such introductory material, which should be easily feasible, would greatly improve the potential of the model as an initial learning tool.

The current model could be used to help student revise and refresh the material they already went through. The idea is that the model may help student « cement » the knowledge they acquired by other methods. Looking at the brachial plexus model as a revision tool, what could be added to improve the model is basic exercises and scenarios to increase the interactivity of the system. A better interactivity will go hand in hand with improved learning outcome. For instance, the student could be asked to touch given bits within the scene. According to the number of right responses the student would get a mark allowing him to keep a track of his progress.

To conclude, tester though that the developed model is a great to supplement either textbook and lectures since the brachial plexus nerves are very difficult to imagine when learned with 2D illustration. However, if the student is not familiar with the brachial plexus a preliminary lecture is still required.

## **REFERENCES**

- [1] T. Persaud. A History of Anatomy: the Post-Vesalian Era. p24. Springfield IL. 1997 ; p24.
- [2] G. Dyer and M. Thorndike. Quidne mortui vivos docent ? The evolving purpose of human dissection in medical education. Academic Medicine, 200 ; p75.
- [3] T. Persaud. A History of Anatomy: the Post-Vesalian Era. p24. Springfield IL. 1997 ; p8.
- [4] J. Older. Anatomy: a must for teaching the next generation. Surg J R Coll Surg Edinb Irel 2. 2004 ; p79–90.
- [5] H. Brenton, J. Hernandez, F. Bello et al. Using multimedia and Web3D to enhance anatomy teaching. Computers & Education. 2007 ; p49.
- [6] J. Perry & D. P. Kuehn. Using cadavers for teaching anatomy of the speech and hearing mechanisms. The ASHA Leader. 2006 ; p11.
- [7] A. Winkelmann & F. H. Guldner. Cadavers as teachers: the dissecting room experience in Thailand. 2004 ; p1455-1457.
- [8] H. Ellis. Teaching in the dissection room. Clin. Anat. 2001 ; p14.
- [9] M. A. Azis, J. C. Mckenzie, J. S. Wilson et al. The human cadaver in the age of biomedical informatics. Anat. Rec., 2002 ; p269.
- [10] G.R. Bernard. Prosection Demonstrations as Substitutes for the Conventional Human Gross Anatomy Laboratory. Journal of Medical Education. Septembre 1972. p47.
- [11] J. Alexander. Dissection Versus Prosection in the Teaching of Anatomy. Journal of Medical Education. August 1970. p45.
- [12] Cognition and Technology Group at Vanderbilt. Anchored instruction and situated cognition revisited. Educational Technology 1993; p52-70.
- [13] <http://www.ramex.com/spec3.html>
- [14] D. E. Cabral & N. J. M. Barbosa. Students' opinions on the use of computer rooms for teaching Anatomy. Int. J. Morphol. 2005 ; p267-270.
- [15] C. Evans, N. J. Gibbons, K. Shah & D. K. Griffin. Virtual learning in the biological sciences: pitfalls of simply putting notes on the web. Comput. Educ., 43, 2004 ; p49-61.
- [16] What lies beneath: the in living anatomy teaching. The Clinical Teacher. Volume 4, Issue 1. February 2007. p10-14.
- [17] <http://www.netteranatomy.com/>
- [18] E . Burmester , T . Leineweber , S . Hacker , U . Tiede , J . Niehaus , T . Huetteroth. EUS Meets VOXEL-MAN a 3-D Anatomical Animation of Longitudinal Endoscopic Ultrasound (L-EUS). Gastrointestinal Endoscopy. Volume 59. Issue 5. p232.
- [19] <http://www.voxel-man.de/>
- [20] G. O. Barnett. Information technology and medical education. J. Am. Med. Inform. Assoc. 1995; p205 - 209.
- [21] C. Rosse. The potential of computerized representations of anatomy in the training of health care providers. Academic Medicine 1995; p499 - 505.
- [22] R. M. Satava. Virtual reality surgical simulator: The first steps. Surgical Endoscopy n°7. 1998 ; p203–205.
- [23] D. Berube, C. Murray and K. Schultze. Cadaver and Computer Use in the Teaching of Gross Anatomy in Physical Therapy Education. Journal of Physical Therapy Education. 1999.
- [24] J. M. Broder. In science's name, lucrative trade in body parts. New York Times. March 12, 2004 ; A1.
- [25] M. A. Azis, J. C. Mckenzie, J. S. Wilson, R. J. Cowie, S. A. Ayeni, B. K. Dunn. The human cadaver in the age of biomedical informatics. Anat. Rec. n°269. 202 ; p20-32.
- [26] N.A. Jones, R.P. Olafson, and J. Sutin. Evaluation of a Gross Anatomy Program Without Dissection. Journal of Medical Education. March 1978 ; 53:3.
- [27] J. C. McLaghlan, J. Bligh, P. Bradley & J. Searle. Teaching anatomy without cadavers. Med. Educ., 2004 ; p38.

- [28] R. Adler. Coursework in anatomy and physiology and neuroanatomy and physiology: what is current and where should we go? *Perspectives on Issues in Higher Education*. 2005. p 3-8
- [29] S. Santana. *Wanted: More Anatomy Instructors*. Association of American Medical Colleges Publications. 2008.
- [30] K.M. Patel & B.J. Moxham, Attitudes of professional anatomists to curricular change, *Clin. Anat.* 19. 2006 ; pp. 132–141.
- [31] A. E. Seyfer, D. Welling, J. P. Fox. The value of surgeons teaching anatomy to first-year medical students. *Bulletin of the American College of Surgeons*, Volume 92, n°10.
- [32] N. W. John. Using stereoscopy for medical virtual reality. *Studies in Health Technology and Informatics*. 2002 ; p85.
- [33] Y. Y. Shieh<sup>1</sup>, C. Benny Jr. Shaw and H. Glenn. Internet Web-Based Teaching for Cross-Sectional Anatomy and Radiological Imaging.
- [34] practical: A stereoscopic 3D interactive multimedia computer examination program. *Clinical Anatomy* 11. p89–94.
- [35] <http://en.wikipedia.org/wiki/Haptic>
- [36] C. Aschwanden, A. Sherstyuk, L. Burgess, K. Montgomery. A Surgical and Fine-Motor Skills Trainer for Everyone? Touch and Force-Feedback in a Virtual Reality Environment for Surgical Training. *Telehealth Research Institute (TRI) Stanford-NASA*.
- [37] M. Hutchins, S. O'Leary, D. Stevenson, C. Gunn, A. Krumpholz. A Networked Haptic Virtual Environment for Teaching Temporal Bone Surgery.
- [38] K. D. Reinig, C.G. Rush, H.L. Pelster, V.M. Spitzer, and J.A. Heath. Real-Time Visually and Haptically Accurate Surgical Simulation. In: *Health Care in the Informatics Age*. IOS Press and Ohmsha, Washington DC., 1996 ; pp 542-545.
- [39] P. J. Fager & P. von Wowern. The use of haptics in medical applications, *Int J Med Robot.* 6 (1), 2004 ; p36-42.
- [40] Phantoms' page on Sensable website :  
<http://www.sensable.com/haptic-phantom-desktop.htm>
- [41] Haptic workstation's page on Immersion website :  
[http://www.inition.com/inition/product.php?URL =product\\_glove\\_immersion\\_hapticworkstation&SubCatID =37](http://www.inition.com/inition/product.php?URL =product_glove_immersion_hapticworkstation&SubCatID =37)
- [42] Immersive's page on sense graphics website  
[http://www.sensegraphics.com/products\\_immersive.html](http://www.sensegraphics.com/products_immersive.html)
- [43] M. Bialeschki. The three Rs for experiential education researchers. *Journal of Experiential Education*. 29(3), 2007 ; p366-368.
- [44] J. Brown. New learning environments for the 21st century: Exploring the edge. *Change*. 2006 September/October ; p18-24.
- [45] H. Gardner. *Frames of mind: The Theory of Multiple Intelligences*. New York: Basic Books. 1983.
- [46] H. Mount, J. Cavet. Multi-sensory environments: an exploration of their potential for young people with profound and multiple learning difficulties. *British Journal of Special Education*, 22(2). 1995 ; p52–55.
- [47] Novint website : <http://home.novint.com/index.php>
- [48] K. L. Moore and A. F. Dalley. *Clinically Oriented Anatomy*, Fifth edition. p781
- [49] Hari Venkatramani et al. Functional outcome of nerve transfer for restoration of shoulder and elbow function in upper brachial plexus injury. *Journal of Brachial Plexus and Peripheral Nerve Injury* 2008 ; p3:15.
- [50] B. McNamara. *ACNR*. Volume 3, n°5. November/December 2003.

## Appendix

Part of Control\_node.h, the header file of the control node, without the includes.

```
namespace H3D {
//*****
//      class declaration
//*****
class control_Node : public X3DChildNode
{
public:

    class colorKey: public TypedField< SFColor, SFInt32 > {
    public:
        colorKey();
        NavigationInfo *mynav;
    protected:
        virtual void update();
    };

//-----

    class colorHapticButton: public TypedField< SFColor, SFInt32 > {
    public:
        colorHapticButton();
        NavigationInfo *mynav;
        X3DViewpointNode * vp;
    protected:
        virtual void update();
    };

//----- STATIC -----

    static int mode;
    static int bmemory;
    static int presetZoom;

//-----
/// The H3DNodeDatabase for this node.
//-----

    static H3DNodeDatabase database;

// constructor

control_Node(

    Inst< colorKey > _key = 0,
    Inst< SFFloat > _infoTransparency = 0,
    Inst< SFInt32 > _strippingLevel = 0,
    Inst< SFInt32 > _strippingLevelMAX = 0,
    Inst< colorHapticButton > _hapticbutton = 0,
    Inst< SFFloat > _transparencyMap1 = 0,
```

```
    Inst< SFFloat > _transparencyMap2 = 0,  
    Inst< SFFloat > _transparencyMap3 = 0,  
    Inst< SFFloat > _transparencyStylus = 0  
);
```

```
//----- Public attributes -----
```

```
    auto_ptr <SFFloat> infoTransparancy;  
    auto_ptr <colorKey> key;  
    auto_ptr <colorHapticButton> hapticbutton;  
    auto_ptr< SFInt32 > strippingLevel;  
    auto_ptr< SFInt32 > strippingLevelMAX;  
    auto_ptr< SFFloat > transparencyMap1;  
    auto_ptr< SFFloat > transparencyMap2;  
    auto_ptr< SFFloat > transparencyMap3;  
    auto_ptr< SFFloat > transparencyStylus;
```

```
protected:
```

```
    virtual void update();  
};  
} // namespace H3D
```