Semester Project

Surgical Tools for the Hysteroscopy Simulator

Author: Michel Estermann
Tutor: Stefan Tuchschmid
Preface

This report is the documentation of my semester project for the minor in “Biomedical Engineering” done at the Computer Vision Laboratory from April 3th until July 14th 2006. This fulfilling semester project provided me a deeper insight into a promising and ambitious topic and I could gain experience in working on a large project with many contributors. Further I could deepen my knowledge on computer graphics and learned to use a powerful 3D modeler.

I would like to thank my tutor Stefan Tuchschmid for his kind support, helpful advices and invaluable suggestions leading to a promising result. Further I would like to thank Dani Bachofen and Bryn Lloyd for their contribution and help.

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Michel Estermann
Abstract

Hysteroscopy is today the standard procedure for the endoscopic inspection of the uterine cavity and belongs to the most often performed procedures in gynecology. The facility to train the various skills required to perform a successful intrauterine surgery with a minimal risk for patients is crucial for the medical apprenticeship. Surgical simulators using virtual reality are a promising alternative to traditional training. For a realistic training environment providing a wide variety of tasks, the operation environment including most surgical tools should be cloned in virtual reality.

Within this semester project two new surgical tools, namely the Rollerball and Knife Electrode were created using the open-source 3D modeler Blender. The rollerball is used for endometrium ablation and hemostasis using a high-frequency current producing enough energy to coagulate the tissue. A model is proposed and implemented to visualize this tool-tissue interaction using texture blending.
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Introduction

Hysteroscopy is today the standard procedure for the endoscopic inspection of the uterine cavity and belongs to the most often performed procedures in gynecology. Hysteroscopy is not only used for diagnostics but also for surgery. Mishandling due to the lack of experience can cause serious complications and leads to bleeding and damage of organs. It is therefore important for surgeons to acquire sufficient skills through repetitive training under various conditions. A promising alternative to traditional training is the surgical simulation using virtual reality, permitting various training scenarios without the risky involvement of patients.

The goal of the Hysteroscopy Simulator project by the National Centre of Competence in Research (NCCR) CO-ME\textsuperscript{1} is, to provide a realistic training environment with the highest possible realism for a wide variety of tasks. In surgical hysteroscopy specialized instruments including probes, miniature scissors and various forceps are used for the different surgical tasks. However, currently 95\% of all hysteroscopic surgery is performed using a resectoscope. Among the most commonly used resectoscopes are Cutting Loop, Rollerball, Rollerbarrel and Knife Electrode. Currently only a Angled Cutting Loop is implemented in the simulator, it is therefore important to integrate more tools in order to provide training for a wide variety of tasks.

Within the scope of this semester project I modeled a Rollerball and a Knife Electrode, also commonly called Needle, and integrated it in the Hysteroscopy Simulator together with the corresponding interaction with the organ’s tissue caused by the rollerball electrode during coagulation.

In chapter 2 a brief introduction in surgical hysteroscopy and the different techniques and instruments used is given. Chapter 3 presents the Hysteroscopy Simulator in which this work will be integrated. The work done within this semester project is presented in chapter 4 together with the achieved results and an outlook on future works needed to improve the realistic look and behavior of the rollerball further.

\textsuperscript{1}Computer Guided and Image Guided Medical Intervention
Surgical Hysteroscopy

2.1 Overview and History

Hysteroscopy is the visualization of the uterine cavity by endoscopy. The hysteroscope is a thin telescope that is inserted through the endocervical canal into the uterus. It consists of a fiber-optical system (today usually connected to a video system), a high-quality cold light source, a channel for delivery of a distention medium and in the case of a operative hysteroscope a channel to hold specialized surgical tools. A hysteroscope allows for the diagnosis of intrauterine pathology and serves as a method for surgical intervention.

Pantaleoni [12] performed 1869 the first hysteroscopy, diagnosing an endometrial polyp with the aid of an endoscope and cauterized it with silver nitrat [2]. Nitze [11] developed 1879 a new kind of endoscope, the Nitze-Leiter cystoscope, with a light source inside the endoscopic tube, which allowed clearer vision and a more intense lightning. Figure 2.1 shows an early version of hysteroscopy described by Duplay and Clado [5]. Although hysteroscopy was one of the earliest approaches to the direct study of the uterine cavity, it did not achieve routine gynecologic use due to its poor optic system and it was not a useful technique until the 1970s when technical improvements in lenses and distention media resolved some of the difficulties that had prevented its widespread use before that time [2]. For a more detailed historical review of endoscopy see [13].

2.2 Basic Principles

For surgical hysteroscopy rigid hysteroscopes with an outer diameter of 7 mm, equipped with two channels are usually used. Through one channel the distention media can be introduced, the other channel can hold instruments including miniature scissors and forceps. Today, however, 95 % of all hysterosopic surgery is performed using a resectoscope.
2.2.1 Resectoscope

Based on the resectoscopes originally used in urology, the gynecological resectoscope is an instrument used to resect and remove intrauterine pathological formations and for endometrial ablation. It consists of a 4 mm-telescope (preferably with a $12^\circ$ direction of view), a continuous-flow sheath with in- and outflow valves for the suction and irrigation of liquid distension media and a channel holding the instrument. Figure 2.2 shows a resectoscope with a continuous-flow shaft. Beside the classical cutting loop electrode, different other instruments such as coagulation or vaporization electrodes of various shapes, e.g. rollerball (figure 2.3) and rollerbarrel, can be connected to the resectoscope.
2.2. Basic Principles

2.2.2 Electrosurgery

Resection and coagulation is performed with high-frequency current producing enough energy in the tissue to coagulate at 60-70 °C or vaporize the tissue at 100 °C. For the thermal cutting of pathological tissue, a continuous unmodulated high frequency current is used, which causes a rapid intracellular temperature rise, causing the treated cells to explode [10]. The current can not pass desiccated tissue and it is therefore unlikely to heat up the tissue deeply. Since the heat vaporizes the distension media and tissue cells, bubbles are created at the cutting site.

For coagulation, a unmodulated current with intermittent periods of electrical activity of higher voltage peaks is used. The intermediate phase without activity, takes up about 80 % of the time. The short activity phase causes cellular dehydration, coagulation of proteins and ensuing hemostasis. The higher voltage allows a deeper penetration of desiccated tissue, while the long intermediate stationary phase decreasing the tendency of gas ionisation and mutilation of local tissue.

Coagulation and Endometrium Ablation

Although cutting loop electrodes can be used for locale hemostasis by applying a intermittent current, electrodes with larger contact surface like rollerballs (figure 2.3) or barrels are usually used for large-area coagulation. Due to the short activity phase and the larger surface, less energy is applied to the tissue, leading to dehydration of the cells and denaturation of proteins. The denaturation leads to the typical white discoloration of the tissue, often referred to as white coagulation. Increasing the applied energy can lead to cauterization and carbonization of the tissue and agglutination of the electrode.

Endometrial ablation can be performed by resection of the endometrium with a cutting loop slice for slice. Alternatively or in combination with resection, a rollerball (or barrel) can be used for endometrium ablation.
Resection of Uterine Septum

Resection of a septum dividing a uterus\textsuperscript{1} is often performed with a needle-shape \textit{Knife} resectoscope with cutting current by carefully dividing the septum. The needle can also be used to treat intrauterine adhesions or to remove small polyps in areas the cutting loop cannot access.

2.2.3 Distension Media

In order to obtain a clear view, the uterine cavity must be distended either by gas oder fluid. Gases are used exclusively in diagnostic hysteroscopy, liquids are used in both diagnostic and surgical hysteroscopy. Electrosurgery is only feasible with electrolyte-free liquid distension media to prevent the electricity from spreading. In resectoscopic hysteroscopy, hypertonic, non-electrolytic solutions, like glycine and sorbitol/mannitol, are used, because they do not conduct electricity, provide a good view and are not very toxic.

2.3 Summary

Hysteroscopy is a commonly used technique in gynecology and resectoscopes are used for various surgical interventions. \textit{Rollerball} and \textit{Knife Electrode} are important resectoscope and often used alone or in combination with other instruments for different surgical treatments. It is important to support this tools in the Hysteroscopy Simulator to allow a variable training environment providing the facility to train different tasks. Coagulation changes the structure and color of the treated tissue dependent on the applied energy. It is therefore indicated to visualize this effect in order to provide a realistic training setting.

\textsuperscript{1}called \textit{septate uterus} by physicians
Hysteroscopy Simulator

The goal of the Hysteroscopy Simulator project by the National Centre of Competence in Research (NCCR) CO-ME is, to provide a realistic surgical training simulator with the highest possible realism for a wide variety of tasks. Currently a prototype is available using several modules. These modules provide simulation of soft tissue deformation, collision detection and response, tissue cutting, a hysteroscopy tool as haptic input device to the simulator and a module for blood flow simulation. Figure 3.1 shows the simulator in the training operation room.

The Hysteroscopy Simulator is written in C++ using the OpenGL and SDL library for the visualization and multimedia control.
OpenGL is a software interface to graphics hardware. The interface consists of over 100 different function calls which can be used to draw complex three-dimensional scenes from simple primitives. For more details how to program with OpenGL see [16] and [15] or the links in A.3.1. Simple DirectMedia Layer (SDL) is a open source cross-platform multimedia library designed to provide low level access to audio, keyboard, mouse, joystick, 3D hardware via OpenGL, and 2D video framebuffer (see A.3.1 for links).

3.1 Simulator Framework

The Hysteroscopy Simulator is a highly modular multi-threaded real-time system. A framework for the simulator based on a object oriented design, thread-based parallelization and a synchronization tool set was designed by Tuchschmid et al. [19], in order to meet the requirements of a flexible, maintainable and extensible real-time system. The domain model includes instances of simulation objects and the simulation engines. The so-called Site Manager schedules the interaction between all components.

3.1.1 Simulation Objects

The surgical scene consists of instances of Deformable Objects, like the uterine cavity and pathological formations and Rigid Objects, like the endoscopic tool. Both types are represented by physics and visualization models (see figure 3.2). The physics model of deformable objects is based on a tetrahedral mesh and used for collision detection, response and the calculation of deformations. For rigid objects no deformation model is needed, but in order to perform collision detection, collections of points are used to approximate the object geometry. The visualization model of both objects is defined by higher resolution triangular surface meshes.

Figure 3.2: Object representations: Physics model (left); visualization model mesh (middle) and with texture and illumination
3.1.2 Main Loop

The Simulator consists of several parallelized simulation engines. The high priority *Main Loop* contains all modules involved in the mechanics of tool-tissue interaction and builds the core of the simulator. The major elements of the main loop are

- Tissue deformation.
- Transformations: Based on the informations of the tissue deformation, the visualization models of the deformable objects and the rigid objects with their corresponding collision meshes are updated.
- Tissue cutting: Adaption of all involved surface and volumetric models, if a cut is performed. If a complete piece of tissue is removed from a deformable object, a new instance is created and registered with the *Site Manager*.
- Collision detection and response: Based on the collision detection, the internal and external forces for soft-tissue deformation and force feedback are determined.
- User interaction: The forces are communicated to the *Device Manager* to control the haptic device.
- Synchronization with lower priority engines.

3.1.3 Simulation Engines

Additional to the main loop the simulator consists of lower priority simulation engines: the *Flow Engine* responsible for the motion of the distension liquid, the *Vision Engine* responsible for the handling and visualization of the surface data and the *Audio Engine*. The highest priority *Device Manager* is responsible for managing the user interaction, possible either by an adapted hysteroscopic tool, a PHANToM haptic device, or mouse and keyboard.

**Visual Engine**

The *Visual Engine* provides a scene graph as interface to the framework. In a scene graph, objects can be linked in a parent-child relation to pass a movement of the parents down to the child [1]. The scene graph consists of two main objects. The main leaf, called the *Shape*, represents a general graphic object in the graphics framework and contains all data about it. A Shape can be added to any other Shape in the tree to represent a parent-child relation. The second objects in the scene graph are called *Face*. A Shape can have
zero or more Faces associated. A Face is a surface of a Shape and can be added to any Shape.
The Shape is responsible for updating the geometry and computes any relevant data.
The two possible objects, Deformable Object and Rigid Object, mentioned in the previous section (3.1.1) are types of Shape.
A Face is responsible for drawing the surface with the data given by the Shape using different maps, i.e. texture, bump and environment map.

3.2 Visual System

The important part needed for this work is the visual system, drawing the scene onto the monitor. I will not explain the other engines in more detail, since I do not have the knowledge to do so and they had no influence on this work.
In this section I will first give a brief introduction to some techniques used in 3D computer graphics in general and then explain where this techniques are applied in the simulator.

3.2.1 Computer Graphics Background

Texture Mapping

A common method for adding surface details is, to map an image, called texture, onto the surface of objects. This allows a complicated coloring of the surface without requiring additional polygons to represent the details. This approach is referred to as texture mapping.

Multitexturing is the use of more than one texture at the time, e.g. bump map, light map and environment map. The texels\(^1\) need to be mapped to points on the 3D object, this is called texture filtering and different filtering methods exists, with bilinear filtering the most commonly used one.
In OpenGL both, texture coordinates and geometric coordinates, need to be specified as the objects in the scene is specified. For a two dimensional texture map the texture coordinates range from 0.0 to 1.0 in both directions, but the coordinates of the items being textured can be anything [16].

Bump Mapping

A method for modeling the surface roughness called bump mapping was proposed by Blinn [3] and is commonly used today. The idea is to apply a perturbation function to the

\(^1\)pixel of a texture
surface normal and then use the perturbed normal in the illumination-model calculation. Bump mapping generates therefore not a real 3D surface, but rather computes the shading based on the height map and draws it like a texture on the polygon. The application of this technique also used in the Hysteroscopy Simulator is called normal mapping or sometimes also referred to as dot3 bump mapping. This technique does not perturb the existing normal, but replaces the normal entirely with a normal taken from a separate texture, called height map or normal map. Based on these normals and the position of the light source, the shading for every single texel is computed.

**Environment Mapping**

Standard environment mapping, more commonly referred to as spherical environment mapping, simulates highly reflective surfaces without using ray-tracing by applying a texture (called sphere or environment map) which represents the entire environment. A sphere map is a single texture of a perfectly reflecting sphere in the environment where the viewer is infinitely far from the sphere. The result approximates the appearance of a real reflecting surface. OpenGL directly supports spherical environment maps. An other approach for environment mapping, called cube environment mapping, is to use not only one texture wrapped around the object, but six textures, arranged like the faces of a cube places around the object. The idea is, that you can capture a 360° view of your surrounding environment, by taking six photographs, each at an orthogonal 90° view from the others.

**Billboarding**

*Billboarding* is a technique in which objects are drawn as simple flat texture mapped geometry and the objects orientation is adjusted, such that it always faces the viewer. This allows to make objects appear 3D, but in fact there are rendered 2D, cutting back the number of required polygons dramatically. Billboarding is often used to render complex objects like trees, which otherwise would require a large number of polygons. It is to note, that the shading for complex objects will not be correct, if the same texture is used for all orientations. Further billboards need to be ordered by depth, since a billboard should usually not be drawn over an other billboard in front of it. Therefore farthest billboards need to be rendered first.

**Alpha Blending**

To create the effect of transparency in computer graphics, alpha blending is used. Alpha blending combines a translucent foreground with a background color to create an in-between blend. To control the opacity of a image pixel, every pixel is represented with
four color channels, red, green, blue and alpha (RGBA). The first three channels define the color and the alpha channel defines the opacity, zero means full transparency while one (or 255) means full opacity.
As blending function, the following normal blending function is applied to each RGB channel to get the resulting color.

\[ \text{color} = \text{color}_{bg} \cdot (1.0 - \text{alpha}) + \text{color}_{fg} \cdot \text{alpha} \]

### 3.2.2 Illumination in the Hysteroscopy Simulator

#### Multipass Rendering

As mentioned in section 3.1.3, the class `Face` is responsible for drawing the surfaces of a object (`Shape`). Currently three pass multipass rendering is used to illuminate the scene, including bump and environment mapping:

**Pass 1** Bump mapping: The rough surface is computed from the height map (bump map) and the generated gray scale picture of the scene is drawn without any textures or materials.

**Pass 2** Spotlight effect: The blank with objects are illuminated with a specular light and an ambient spotlight and modulated with the general illuminated scene.

**Pass 3** Texture and environment map: The complete scene is rendered with general light (ambient, diffuse and specular), material properties and textures, including the environment map. Multitexturing is used to combine the texture with the environment map. The result is added to the images from the first and second pass.

#### Bubbles, Blood & Tissue Craps

Billboarding is used to simulate bubbles, blood and tissue craps. Blood and bubbles are a simple type of billboards. They do not require any illumination and don’t have to be sorted, since they all look the same and alpha blending of the billboards still looks correct. Tissue craps are more difficult billboards, they need the same illumination model as the surface they are connected to and need to be sorted, since a tissue billboard can’t be drawn over another billboard that lies in front of it (see also 3.2.1).

#### Soft Tissue Deformation, Collision Detection and Tissue Cutting

Soft tissue deformation is an important component in the Hysteroscopy Simulator. The model used in the simulator considers elastic and plastic deformation and is described
in [17] by Teschner et al. They consider deformable solids discretized into tetrahedron and mass points and compute the dynamic behavior of objects by deriving the forces at the mass points from potential energies.

For a realistic interaction between soft tissue and solid objects, efficient collision detection algorithms are required. Teschner et al. proposed in [18] an algorithm that classifies all object primitives with respect to small axis-aligned bounding boxes (AABB) and uses a hash function that maps 3D cells to a hash table.

For this semester project the details of the soft tissue deformation and collision detection algorithms are not relevant. For more details I reference to the cited articles.

A key element in training of surgical hysteroscopy is the ablation and resection of tissue and pathological formations, therefore the interactive simulation of soft-tissue cutting is an integral part of the Hysteroscopy Simulator. Harders et al. [6] combined the mesh subdivision and mesh adaption approaches for the simulation of soft tissue cutting and optimized them for the hysteroscopy simulator.

The rollerball created within this work does not allow cutting of soft tissue, but the knife electrode does. However the cutting approach currently used in the simulator is not applicable for the knife, since the hybrid approach mentioned is carried out as the tool leaves the tissue. This simplification is reasonable for the cutting loop, since the loop electrode is usually placed behind the pathology and then advanced towards the camera, but this is usually not the case when using a Needle to divide a septum. Since a solution to this problem can not be solved within this project, I didn’t study the cutting approach in more detail.
Creating a New Surgical Tool

4.1 Necessary Steps to Create a New Tool

The following necessary steps to create and integrate a new tool into the hysteroscopy simulator can be identified:

1. Three different tool representations need to be modeled. Namely the high resolution visual representation, a low resolution approximation of the tool for collision detection and an approximation of the tool electrode for performing cuts and coagulation.

2. The models must be exported as wavefront object files and modified to be readable by the Object Loader of the Hysteroscopy Simulator.

3. A new C++ class needs to be added to the simulator framework, defining all the properties and behavior of the tool.

4. The tissue interactions and responses need to be implemented.

4.2 Modeling with Blender

4.2.1 Introduction

Blender\(^1\) is a powerful open source software for 3D modeling and was used in this semester project to model the rollerball and knife electrode. Blender is aimed at media professionals and artists and can be used for 3D modeling, animation, rendering,

\(^1\)www.blender3d.com
4. Creating a New Surgical Tool

4.2.2 Steps for Modeling a new Hysteroscopy Tool with Blender

The Hysteroscopy Simulator uses the wavefront object file (.obj) and material library file (.mtl) formats as model description. Blender can import and export various file formats including wavefront object and material library files, if the necessary python scripts are installed. The scripts are usually provided with the standard blender installation, but if there is no menu entry to import (export) .obj files, you have to specify the path to the python scripts in the user preferences window in order to register them.

Object Models

The Hysteroscopy Simulator requires three object models (see figure 4.1). A visualization model for the visual system, a collision model for the collision detection and a interaction model to perform cuts and coagulation (see also section 3.1). The visualization model is the high resolution triangular surface representation of the tool, used to visualize it with OpenGL (figure 4.1 left). For the collision detection a low resolution approximation of the object geometry is needed. To represent the collision model, the tool — including body, mount and electrode — is modeled with a number of cubes (figure 4.1 middle). For post-production, interactive creation and playback [4]. Because of its power and many functions it is difficult to start without any help and the non-standard concept of the interface needs some introduction to use it efficient. However after working through some basic tutorials, basic 3D objects can easily be modeled. I will not provide a introduction and manual to modeling with blender, since there are many good tutorials and manuals freely available2. However I will point out some important steps and pitfalls to be considered in order to produce models usable for the Hysteroscopy Simulator. The following guidance refers to Blender version 2.4 and can be different to previous versions.

Figure 4.1: Models of the rollerball required for the Hysteroscopy Simulator. left: visualization model; middle: collision model; right: interaction model

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2see mediawiki.blender.org/index.php/Main_Page
the interaction model only the vertices representing the electrode in the collision model are used. To get the object file for the interaction model we therefore export the approximation of the electrode (figure 4.1 right) and later remove manually all the vectors and faces in the object file, keeping only the vertices defining the interaction points.

Following are some steps and hints good to have in mind for modeling a new tool that can be integrated into the simulator without problems:

- It's best to import an existing tool as a starting point for a new tool and then modify the model to create a new tool.
- For most tools it's advantageous to utilize the symmetry of the tool and model only one half and then use the mirror modifier to complete.
- Wires like the mount or a cutting loop are best modeled as curves, either NURBS or Bezier and then the “extrude along path” technique can be used to extrude a circle along this curve and form a pipe.
- It's important to convert all pipes, created from curves, into meshes before exporting the object. After converting the curve, the associated circle can be deleted.
- Since the Hysteroscopy Simulator can only handle triangular faces. All meshes containing quads must be converted into triangles.
- All faces should be set to smooth rendering.
- Be sure to assign texture per face (“make TexFac”) for each object, otherwise there will be no texture vertices in the exported object file, generating errors by the ObjLoader of the simulator, since the loader expects this vertices.
- Don’t forget to delete all unnecessary objects like camera and light source before you export the model. Otherwise all vertices of this objects will also be included.
- It's a good advice to name all objects, such that you easily can identify the associated vertices and vectors in the resulting object file.
- Assign to all objects a material and give it a name in order to be easily identifiable in the corresponding object and material library file
- It's good to group the objects of any tool into three groups, e.g. body, mount and ball in the case of the rollerball and assign them three different materials, e.g. body, mount and wire.
- If meshes are created out of curves or meshes like spheres are used, they consist usually of many vertices and faces. It’s recommended to decimate the objects reasonable in order to reduce the number of vertices and faces as much as possible without reducing the visual smoothness too much.
• Calculate the normals new (outside), to make sure that they are pointing in the right direction.

Modifying the Object File

The object file exported by Blender is different to the ones expected by the ObjLoader of the simulator, therefore it has to be slightly modified:

• Blender lists the vertices, vectors and faces in groups for every object. At the top the object name is given (e.g. o mount) followed by the geometric vertices (v), texture vertices (vt) and vertex normals (vn). The object name is not used by the ObjLoader of the simulator, but helps us to identify the different parts of the tool.

• Blender doesn’t specify groups in the object file, but the simulator expects them. The loader want load faces if they are not part of a group. In order to build a group, add a group name (e.g. g mount) right after the normal vectors and before the material name (usemtl).

• If the the group is not a smoothing group (s off), enable smoothing (s 1).

• Check that all faces are “three-sided” and that the texture vertices are also referenced, i.e. entries have the form “f 1/1/1 2/2/2 3/3/3” and not “f 1/1/1 2//2 3//3”. If this isn’t the case, we forgot to convert quads to triangles and/or forgot to assign texture per face (see previous section).

• Check that the material names (usemtl) in the object file (.obj) correspond to the names in the material library file (.mtl).

4.2.3 Summary

Blender is a good solution for modeling new tools for the Hysteroscopy Simulator, since it is very powerful and freely available for various platforms. It takes some time to start with, but after getting more into it, it allows for easy modeling and modification of 3D objects. That the exported object files need to be modified slightly is considered to be only a minor drawback. Figure 4.2 shows a screenshot of the rollerball modeled in Blender and figure 4.3 shows the same tool rendered by Blender.

The cutting loop and camera currently used in the Hysteroscopy simulator were modeled with the shareware “MilkShape 3D”, however it is only available for Windows and I didn’t look at it, but it may be an alternative to Blender.
4.3 Tool Classhierarchy

When I started this semester project, the cutting loop was the only tool implemented, beside a forceps not used any more. The class representing the cutting loop was called tool2 and inherited from RigidObject, iKeyboardListener and Knife. The class tool2 was already a specialized class, with all the properties and behavior of the cutting loop. With this class hierarchy, integrating a new tool with different behavior would mean to implement a new class with new, but also many identical properties and behavior as tool2, or, alternatively, the new tool could inherit from tool2 and override the behavior different from the cutting loop tool. Both approaches do not reflect proper object-oriented design and are not recommended. All resectoscopes share some properties and behavior, but differ in others. The rollerball for example can not be used to cut tissue, nevertheless the high frequency current used for cutting with the cutting loop can be applied when using the rollerball, but resulting in a different tissue interaction. Moreover, since more tools will certainly be implemented in the future, a proper class hierarchy for tools is needed.

Figure 4.2: The rollerball in Blender
To better reflect the relationship among different tools, the class hierarchy was redesigned within this semester project. Figure 4.4 shows this new hierarchy. The class ElectroTool is the baseclass for all resectoscopes used in electrosurgery and all tools that are connected to a high-frequency electrosurgical generator should inherit from this class. tool2 got a more intuitive name and is now called CuttingLoop. This class hierarchy is still not perfect, but the idea was to change the current framework as less as possible to avoid compatibility problems.

### 4.4 Rollerball: Tissue Interaction

#### 4.4.1 Idea

As mentioned in section 2.2.2, using the rollerball for endometrium ablation, leads to desiccation of the tissue and denaturation of the proteins, visible as white discoloration. The visual effect is similar to using a digital brush to paint over an image, available in image and graphics editing applications. However the discoloration should not be a sim-
Figure 4.4: Tool class hierarchy
4. Creating a New Surgical Tool

Figure 4.5: Visualization of the tissue coagulation using blending: The texture of the organ (left) is blended with a second texture resembling the coagulated tissue (middle). The opacity of the second texture decreases with increasing distance to the coagulation point (right).

ple white, but should have some variation and structure and depend on the distance to the interaction point.

The idea pictured in figure 4.5 is, to use *alpha blending* (see 3.2.1). A second texture, called *overlay texture* (or *blend texture*) resembling the coagulated tissue, is lain over the texture of the organ. First, this *overlay texture* is fully transparent and blending it with the original texture of the organ has no visual effect. While coagulating at a point, the opacity of the overly texture is increased depending on the distance to the coagulation point. At the coagulation point we have maximal opacity while opacity decreases with increasing distance to the coagulation point. A similar approach was proposed by Shen et. al. [14] for the visualization of irrigation in a surgical wound debridement simulator and they achieved good results.

4.4.2 Implementation

Texture Blending

A first approach to blend the two textures was, to use multitexturing on the graphic card. Multitexturing is already used to combine the environment map with the object texture (see 3.2.2). The idea was to update the alpha values in the overlay texture for texels within the coagulation area and use an additional texture stage to combine the overlay texture with the base texture. However, we need to keep track of the changed texels, otherwise we may overwrite one that was already updated before. This is of course desired, if the opacity is increased, but certainly not if we overwrite a texel with one with less opacity. Therefore we have to keep the image of the overlay texture in memory, update this image first and then change the texture accordingly. Whenever a texel should be updated, we first check the current alpha channel of the *overlay image* pixel and update the
4.4. Rollerball: Tissue Interaction

Figure 4.6: Tissue Interaction: The color of every texture image pixel within the coagulation area is combined with the corresponding color of the overlay image pixel and the updated area is then passed to the GPU which changes the corresponding part of the texture.

texel only, if the resulting value will be larger. This approach exploits the multitexturing and blending facilities of the graphic card, but needs more graphic card memory, since an additional texture must be saved.

In order to save memory on the graphic card for the future use of higher resolution textures, we decided not to use the OpenGL multitexturing for blending the additional overlay texture with the base texture. The approach chosen to implement the visualization of the coagulation is pictured in figure 4.6 and works as follows:

First, the Rollerball object requests the paths to the texture images (base texture, overlay texture and bump map) from the organ (which is a Shape) and loads them. If the rollerball enters the tissue and the coagulation (or cutting) current is activated, the coordinates of the coagulation point are determined and the corresponding texture coordinates computed. The color of every texture image pixel\(^3\) within the coagulation area is combined with the color of the corresponding overlay image pixel and saved in the local copy of the organ’s texture image. The updated area is then passed to the Face of the organ which in turn passes the pixels to the graphic card using the OpenGL function glTexImage2D. The texels of the texture held in the memory of the graphic card are then updated accordingly.

\(^3\) For this and the following sections, pixel corresponds to the pixel of an image kept in main memory, while texel corresponds to the pixel of a texture kept in the texture memory of the graphic processing unit (GPU)
The color of every pixel (texel) within the coagulation area is calculated using the normal blending function

\[ color(x, y) = color(x, y)_{\text{base}} \cdot (1.0 - \text{opacity}) + color(x, y)_{\text{blend}} \cdot \text{opacity} \]

with \( color(x, y)_{\text{base}} \) the color of the pixel at the position \((x, y)\) in the organ’s texture image, \( color(x, y)_{\text{blend}} \) the pixel’s color of the overlay image and \( \text{opacity} \) the opacity calculated as

\[ \text{opacity} = 1 - \frac{\sqrt{(x - x_0)^2 + (y - y_0)^2}}{r_{\text{area}}} \]

with \((x_0, y_0)\) the coagulation point, \((x, y)\) the pixel, and \(r_{\text{area}}\) the radius of the coagulated area.

The above formula decreases the opacity linearly with increasing distance to the coagulation center. As alternative logarithmic functions of the form

\[ \text{opacity} = \log \left( \frac{\sqrt{(x - x_0)^2 + (y - y_0)^2}}{r_{\text{area}}} \right) \log u , \quad \text{with} \; u \ll 1 \]

can be used to produce a more blurry area.

Different blending functions as presented in [8] have been tried, but the Normal blending function produced the best result with the overlay texture used. However with a different (more whiter) overlay texture, Color Dodge\(^4\) and Lighten\(^5\) may produce similar or even better results.

**Coagulation Area**

The radius of the coagulation area is time-dependent, i.e. if the electrode stays at the same point while high-frequency current is supplied, the energy spreads deeper into the tissue, heating up the cells in a wider area. Videos from a rollerball in action showed, that this area spreads not continuously, but more in discrete time steps. Whether this is always the case and why the energy spreads like this, needs to be investigated further. However, to reflect this effect, the radius is increased every second by half the initial radius, but the radius may not exceed twice the initial radius. It is to note that this values are randomly chosen, since I do not have the experience to estimate them and they should be tuned to reflect more closely the reality.

\(^4\text{base} \cdot (1 + 254 \cdot \text{blend}/255)\)

\(^5\text{choosing the lightest value of the base and blend colors in each channel}\)
Determination of the Coagulation Point’s Texture Coordinates

The determination of the texture-space coordinates closest to the collision point, i.e. where the tool touches (enters) the organ, is performed by the Shape, since Shape holds all the data about an object (the organ in our case). To determine the coagulation point’s texture-space coordinates, we first search for the triangle closest to the collision point by iterating through all triangles. Since the Shape knows the texture coordinates at the triangle vertices, we can now interpolate to find a close approximation of the collision point’s texture coordinates.

Normal Map

The discoloring of the texture alone, didn’t produce a stunning effect, therefore the normal map is updated accordingly in addition to the texture update. This is done by creating a small normal map — the size of a square surrounding the coagulation area — forming a bowl with the diameter of the coagulated area. This normal map is then combined with the original bump map, using a normal blending function similar to the one used for the texture blending. This approach does of course not really reflect a shrunken tissue, but produced a reasonable visual effect, when the opacity was clipped to a maximal value smaller than 0.5.

Cutting Current vs. Coagulation Current

As mentioned in 2.2.2, too high energy applied to the tissue, can cause cauterization and carbonization rather than denaturation. This is the case, if constant cutting current is applied instead of intermittent coagulation current. This effect is reflected in this model by darken the overlay image when applying cutting current.

The Joint Problem

Since the texture is wrapped around the object, every surface has a edge where the texture sides are joined. If we coagulate close to this joint, we have the problem, that the texels on both sides must be updated, otherwise the joint will become clearly visible. A solution to this problem is not straight forward, since the texture isn’t mapped to the organ as a square. Therefore we can not simply jump to the start (or end) of the image row (or column) to continue the texel update.

I could not solve this problem within the scope of this semester project, but an idea how to solve it could look as follows:

From the collision point in object-space we move in every of the four directions (north,
east, south and west) on the surface plane orthogonal to each other the length of the coagulation area radius and determine the coordinates in texture-space at the new positions. If the distance between two points in texture-space is exceptionally large, we certainly crossed the joint and we need to coagulate at this mirror point as well. The problems is how fare we have to move in object space in order to get the right mirror point in texture space. Since the radius of the coagulation area is currently specified as number of pixels in the texture image, we need to transform the corresponding coagulation area radius into object-space. The second problem is, that the four directions in object-space need to correspond to the directions in texture space, since we have to move in object- and texture-space accordingly. If we could easily map all points in object space exactly to the corresponding point in the texture-space and vice versa, both problems could be solved. However this is not the case yet and therefore the problem is left open for future work.

Bubbles and Tissue Craps

During coagulation many bubbles are created, due to the vaporization of the distension media and cell liquid. Two bubble pools are used to create bubbles at both sides of the rollerball. In addition bubbles are created in line of the coagulation point, but closer to the viewer, in order to be in front of the ball. Since the interaction of the bubbles with objects is not implemented yet, the bubbles would move through the ball otherwise. Currently no tissue craps are connected to the ball. However releasing or connecting tissue craps to the rollerball during coagulation could probably improve the appearance.

4.5 Results

Figures 4.7 to 4.10 show the newly modeled and into the Hysteroscopy Simulator integrated tools, Rollerball and Knife (or Needle) Electrode. Both have a nice visual appearance and the soft tissue deformation works fine for both tools. With the Rollerball it’s possible to ablate the tissue by applying coagulation or cutting current, resulting in white coagulation of the tissue if the correct current is applied or carbonization, if to much energy is used. Figure 4.11 shows the rollerball during coagulation and the resulting coagulated tissue. Figure 4.12 shows the coagulated area with full illumination and only the illuminated bum map. The Needle does not yet provide any interaction with the tissue besides the soft-tissue deformation, since the cutting of tissue needs to be implemented different than for the cutting loop and is therefore left open for future work (see also 3.2.2).
4.5. Results

Figure 4.7: Side view of the new *Knife Electrode* (or *Needle*) in the Hysteroscopy Simulator

Figure 4.8: Camera view of the new *Knife Electrode*
Figure 4.9: Camera view of the new Rollerball Electrode

Figure 4.10: Side and close up camera view of the new Rollerball Electrode
Figure 4.11: *Rollerball Electrode* during coagulation (left) and the result of the coagulation (right).

Figure 4.12: *Rollerball Electrode* tissue interaction. The coagulated area with full illumination (left) and only the illuminated bum map (right).
4. Creating a New Surgical Tool

4.6 Conclusion

The task of this semester project has been to model and integrate new surgical tools for the Hysteroscopy Simulator. Two new tools, namely a Rollerball and Knife Electrode, commonly also referred to as Needle, were created using Blender and a framework for an easy integration of the tools into the Hysteroscopy Simulator was designed. The tools created can be used as they are and build a good base for modeling other tools. The new class hierarchy for electrosurgical tools reflects better the relations between the different tools and provides a flexible and extensible framework for future implementations. The interaction of the rollerball with the tissue, i.e. the coagulation of the endometrium, still needs some fine tuning and some problems need to be solved. However the approach taken is a good and reasonable working base to build upon. The integration of new tools was a small but nevertheless important step closer to the ambitious goal to provide a highly realistic training environment. New surgical scenarios are possible with the Rollerball, and more skills can be trained.

4.7 Future Work

As mentioned in section 4.4.2, the problem of the outstanding edge when coagulating close to the texture joint, needs to be solved. A easy and fast mapping of all object-space coordinates to the corresponding texture-space coordinates and vice versa, could probably solve this problem. Moreover, this would also allow a more accurate coagulation point determination. Currently the rollerball allows only the coagulation of uterus tissue, but not of pathological formations like polyps and myomas. The implementation needs therefore to be extended to allow coagulation of all tissues. Further the coagulation point must be constraint to collision points part of the interaction model, but both should easily be possible. To achieve a better and more realistic effect it should be experimented with different overlay textures and normal maps and the time dependent coagulation area radius should be tuned to reflect the reality closer. Moreover a plastic deformation of the organ mesh should be considered to reflect the tissue ablation. To visualize the rotation of the rollerball during coagulation it should be considered to apply a texture or bump map to the rollerball, and rotate the ball when performing movements along the cavity wall.
URLs

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A.2 Blender

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A.3  Hysteroscopy Simulator

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CO-ME
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Medical Interventions http://co-me.ch/

A.3.1  OpenGL, SDL

OpenGL official website http://www.opengl.org/
SGI’s OpenGL website http://www.sgi.com/products/software/opengl/
NeHe OpenGL Tutorials http://nehe.gamedev.net/
SDL homepage http://www.libsdl.org/index.php
SDL Tutorials by Andrew http://andrew.textux.com/Articles.html
Medical Glossary

Figure B.1: Schematic frontal and side view of female anatomy (source: wikipedia.org)

- **abdomen** The belly, or that part of the body between the thorax and the pelvis
- **ablation** elimination or removal
- **bicor-nuate** having two horns or horn-shaped branches
- **bicor-nuate uterus** a congenital malformation of the uterus where the upper portion (horn) is duplicated
- **cervix (cervix uteri)** “neck of the uterus”. The opening between the uterus and the vagina (see figure B.1)
- **coagulation** in general the clumping together of particles. Coagulation of blood: when the liquid blood becomes solid clots
- **cornual** horn shaped
- **cornu (cornua)** horn
- **cystoscope** endoscopy of the urinary bladder via the urethra
- **debridement** removal of dead, damaged or infected tissue
denaturation in biochemistry, a structural change in macromolecules caused by extreme conditions like heat or chemicals

distention media media to expand (distend) a cavity

ettocervix lower intravaginal portion of the cervix (also called exocervix or portio vaginalis)

electrosurgery application of high-frequency electric current to human (or other animal) tissue in order to remove or cut pathological formations or tissue

endocavitory within a body cavity or organ

endocervical canal (endocervix) The cavity of the cervix. Connects the external os with the internal os.

documental having to do with the endometrium

endometrium inner membran (tissue) lining the uterus.

external os opening of the cervix into the vagina (ostium uteri, external orifice of uterus).

fallopian tubes fine tubes leading from the ovaries of female mammals into the uterus (see figure B.1)

gynecology branch of medicine specializing in the medical problems of women, especially disorders or the reproductive organs.

hemostasis process whereby bleeding is halted.

internal os opening of the cervix into the uterine cavity.

intramural literally, “within the wall”.

intrauterine inside the uterus

mucosa a membrane which secretes mucus. It forms the lining of various body passages that communicate with the air.

mucous membrane see mucosa

mucus clear liquid made by intestines that coats and protects tissues.

myoma a tumour comprised of muscle tissue, commonly occurring in the uterus.

ovaries small egg-producing reproductive organs placed on either side of the uterus (see figure B.1).

pathology any deviation from a healthy or normal condition; abnormality.

pelvis The large compound bone at the base of the spine that supports the legs.

polyp a benign (good-natured) tumor protruding from a mucous membrane

resect cut something out

resection surgical removal of a part.

resectoscope a surgical instrument used for performing a resection.

salpinges (salpinx) see fallopian tubes
<table>
<thead>
<tr>
<th><strong>term</strong></th>
<th><strong>definition</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>septate</td>
<td>divided. A <em>septate uterus</em> is a uterus divided in two hemi-cavities by a septum.</td>
</tr>
<tr>
<td>septum</td>
<td>A wall (membrane) separating two cavities.</td>
</tr>
<tr>
<td>thorax</td>
<td>region of the body between the neck and abdomen as well as the cavity containing the heart and lungs.</td>
</tr>
<tr>
<td>transabdominal</td>
<td>literally, (going) “through the abdomen”</td>
</tr>
<tr>
<td>transcervical</td>
<td>literally, (going) “through the endocervical canal”</td>
</tr>
<tr>
<td>unicornuate</td>
<td>having one horn-shaped branch</td>
</tr>
<tr>
<td>urethra</td>
<td>the tube, which connects the uterine bladder to the outside of the body (see figure B.1).</td>
</tr>
<tr>
<td>urinary</td>
<td>pertaining to urine, its production, function, or excretion.</td>
</tr>
<tr>
<td>urology</td>
<td>branch of medicine that treats disorders of the urinary tract and the urogenital system</td>
</tr>
<tr>
<td>urogenital</td>
<td>relating to the urinary and/or the genital systems</td>
</tr>
<tr>
<td>uterine cavity</td>
<td>see uterus</td>
</tr>
<tr>
<td>uterus</td>
<td>major female reproductive organ in which the young are conceived and developed until birth (see figure B.1)</td>
</tr>
<tr>
<td>vagina</td>
<td>the passage leading from the opening of the vulva to the cervix of the uterus (see figure B.1)</td>
</tr>
<tr>
<td>vulva</td>
<td>external female sexual organs.</td>
</tr>
</tbody>
</table>

Bibliography


