

Faculty of Medicine
Biomedical Engineering

Master of Science Thesis

3D Liver Reconstruction from Tracked Ultrasound

by

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Bern, October 2018

Abstract

The abstract should provide a concise (300-400 word) summary of the motivation, methodology, main results and conclusions. For example:

Osteoporosis is a disease in which the density and quality of bone are reduced. As the bones become more porous and fragile, the risk of fracture is greatly increased. The loss of bone occurs progressively, often there are no symptoms until the first fracture occurs. Nowadays as many women are dying from osteoporosis as from breast cancer. Moreover it has been estimated that yearly costs arising from osteoporotic fractures alone in Europe worth 30 billion Euros.

Percutaneous vertebroplasty is the injection of bone cement into the vertebral body in order to relieve pain and stabilize fractured and/or osteoporotic vertebrae with immediate improvement of the symptoms. Treatment risks and complications include those related to needle placement, infection, bleeding and cement extravasation. The cement can leak into extraosseous tissues, including the epidural or paravertebral venous system eventually ending in pulmonary embolism and death.

The aim of this project was to develop a computational model to simulate the flow of two immiscible fluids through porous trabecular bone in order to predict the three-dimensional spreading patterns developing from the cement injection and minimize the risk of cement extravasation while maximizing the mechanical effect. The computational model estimates region specific porosity and anisotropic permeability from Hounsfield unit values obtained from patient-specific clinical computer tomography data sets. The creeping flow through the porous matrix is governed by a modified version of Darcy's Law, an empirical relation of the pressure gradient to the flow velocity with consideration of the complex rheological properties of bone cement.

To simulate the immiscible two phase fluid flow, i.e. the displacement of a biofluid by a biomaterial, a fluid interface tracking algorithm with mixed boundary representation has been developed. The nonlinear partial differential equation arising from the problem was numerically implemented into the open-source Finite Element framework *libMesh*. The algorithm design allows the incorporation of the developed methods into a larger simulation of vertebral bone augmentation for pre-surgical planning.

First simulation trials showed close agreement with the findings from relevant literature. The computational model demonstrated efficiency and numerical stability. The future model development may incorporate the morphology of the region specific trabecular bone structure improving the models' accuracy or the prediction of the orientation and alignment of fiber-reinforced bone cements in order to increase fracture-resistance.

Acknowledgements

Here you may include acknowledgements.

Ich erkläre hiermit, dass ich diese Arbeit selbständig verfasst und keine anderen als die angegebenen Hilfsmittel benutzt habe. Alle Stellen, die wörtlich oder sinngemäss aus Quellen entnommen wurden, habe ich als solche kenntlich gemacht. Mir ist bekannt, dass andernfalls der Senat gemäss dem Gesetz über die Universität zum Entzug des auf Grund dieser Arbeit verliehenen Titels berechtigt ist.

Bern, October 31th 2018

Luca Sahli

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Chapter 1

Introduction

1.1 Motivation

The goal of computer assisted surgeries is to reduce the time used to do the surgery and to also improve the surgical result for the patient. In the case of surgeries involving liver resections, navigation systems are rarely used because they do not provide enough advantages compared to the additional time needed to set them up. The accuracy of such navigation systems is affected by deformations of the liver during the surgery [12]. Additionally for registration based methods is the registration error and the time used to register the patient's anatomy to the preoperative 3D-model of the liver. Supplementary these preoperative 3D-models are very expensive and time consuming to generate. Therefore we aim to develop a new concept to navigate during liver resections. This concept should not need a preoperative scan and would therefore not need a registration. That way we would avoid the expensive and time consuming preoperative 3D-model.

1.2 The Liver

1.2.1 Liver Anatomy

The human liver overlies the gallbladder, is located in the right upper quadrant of the abdomen and has different functions. It produces biochemicals necessary for digestion, synthesizes proteins and detoxifies various metabolites. A human liver weighs normally around 1.5 kg, is the heaviest internal organ and the largest gland of the human body. Two large blood vessels are connected to the liver: the portal vein and the hepatic artery. Both of them subdivide into small capillaries called *liver sinusoids* and then lead to the functional units of the liver known as *lobules*. To refer to the different parts of the liver, it is subdivided into eight subsegments. Each segment has its own vascular inflow and outflow.

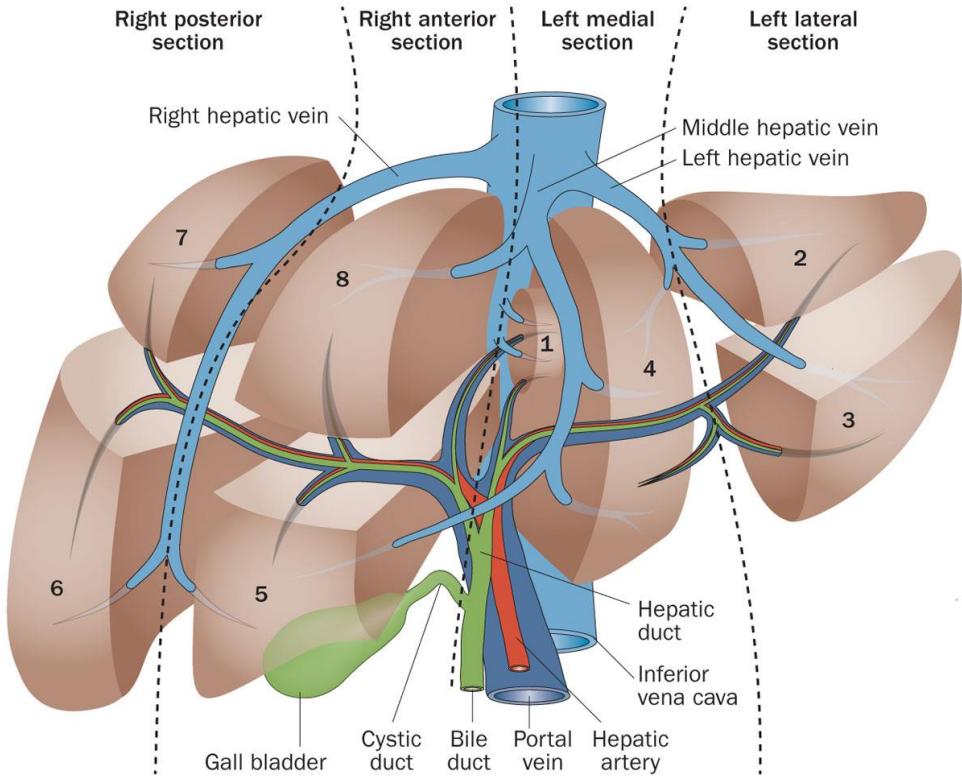


Figure 1.1. The liver and its eight Chouinard segments. In red is the hepatic artery which transports blood from the heart a into the liver. In dark blue the portal vein, it transports blood from the gut into the liver. All the blood leaves the liver through the hepatic veins to the vena cava [36].

1.2.2 Liver Cancer

Liver cancer is cancer that starts in the liver. If the cancer has spread from elsewhere to the liver, then it is known as liver metastasis. Liver metastasis are about 20 times more common than primary tumors. One of the reasons for that is the rich blood supply of the liver which helps the tumors to grow [30]. Liver cancer patients often have chronic liver diseases such as cirrhosis, problems of alcohol abuse, and viral hepatitis (B or C) [17]. The gold standard to treat liver cancer are surgical resections [24]. The liver tissue can easily regrow, given that after resection there is enough healthy tissue and blood supply preserved. Alternatively to resections one can treat liver tumors by local ablation. Both variants treat the tumors with a safety margin of 10 mm. This safety margin ensures that all tumor cells are destroyed and to prevent further spread of cancer cells [28].

1.3 Liver Resections

Hepatectomy is the surgical resection (removal of all or part) of the liver. Liver resections are considered major surgeries and are done under general anesthesia. Most hepatectomies are done laparoscopically. However for complicated cases also open surgeries are done [10].

Two resection techniques can be separated. Anatomical or parenchymal-sparing resections. This work will concentrate on the latter technique.

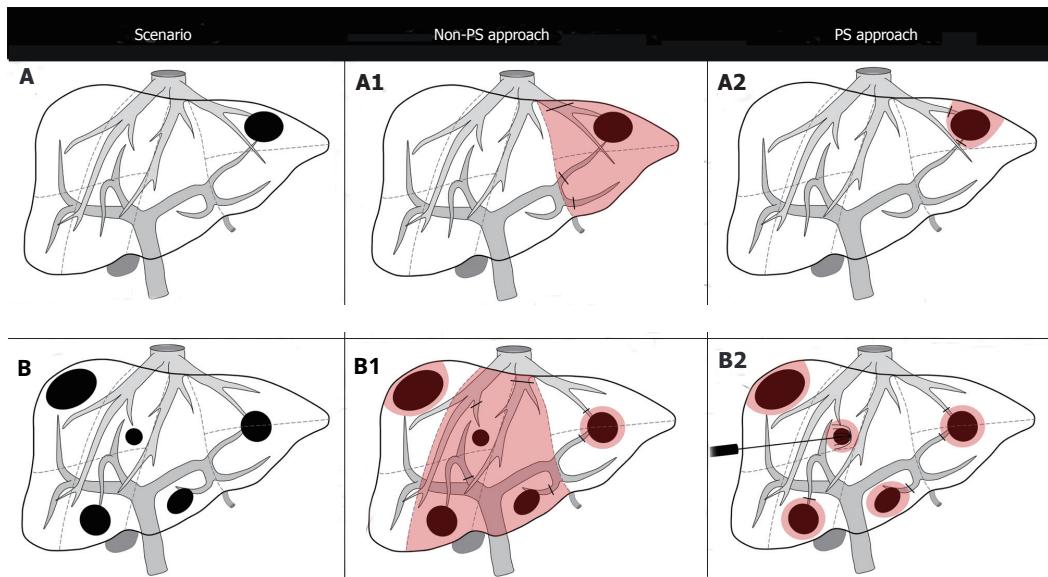


Figure 1.2. Two different approaches to resect liver tumors in two different situations. The *Scenario* column shows the situation of the patient's liver, the *Non-PS approach* column shows how an anatomical resection plan would look like and the *PS approach* column shows how a parenchymal-sparing resection plan would look like [6].

1.3.1 Parenchymal-sparing liver surgeries

[6]

1.4 Objectives

The objectives of this Master's thesis are:

- Implementation of the concept for an intraoperative 3D reconstruction technique of the liver from intraoperative ultrasound.
- Implementation of the intraoperative resection planning.

This work focuses on open surgical procedures of liver hepatectomies and especially parenchymal-sparing methods.

Chapter 2

State of the art

2.1 Intraoperative ultrasound

Ultrasound imaging works by the *pulse-echo* principle. A short ultrasound-pulse is emitted from a transducer. Then the soundwaves get transmitted and reflected differently by different tissues. The reflected soundwaves travel back into the transducer and get converted into an electrical signal. After post-processing these signals become ultrasound images. Basically the ultrasound measures the mechanical properties of the tissue. The tissues have different acoustic impedance, which is the product of tissue density and ultrasound speed in travelling through the tissue. The resolution of the ultrasound images depends on the frequency of the ultrasound waves. High frequencies lead to high resolutions but low depth into the tissue because the absorption of the sound energy increases with frequency too. Therefore the useability to see deep structures is limited [38]. In liver surgeries the ultrasound is used for intraoperative planning and navigation inside the liver. Figure 2.1 shows an example of an ultrasound image of the liver and its corresponding position in the 3D liver model. The surgeon can find the tumors inside the liver by using the ultrasound. Registration methods based on 3D ultrasound reconstructed liver vessels also exist but are not used in practice a lot yet [22]. Therefore ultrasound is an important and established instrument in liver surgeries.

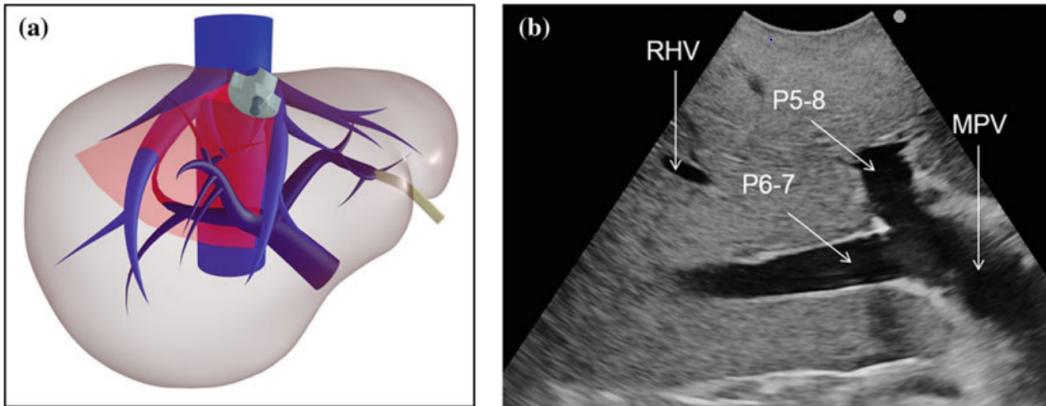


Figure 2.1. Left (a) ultrasound image plane in the liver. Right (b) intraoperative ultrasound image. One can see the right hepatic vein (RHV), the portal branch to segments 5 and 8 (P5-8) and the portal branch to segments 6 and 7 (P6-7) [38]

2.2 Navigation for liver resections

The actual intervention in computer assisted surgeries (CAS) is defined as surgical navigation. For navigated surgeries special instruments are used. These instruments are tracked by the naviagation system. The orientation and position of the instruments in relation to the patient's anatomy is visualized on a monitor in the operating room. The surgeon can then see what he does on the monitor and uses the system to navigate the location and position of its instruments. This is specially then useful when the tip of the instrument is not actually visible for the suergeon. In liver surgeries, the navigation is mostly done by first registering the patient to a pre-operative 3D computer tomography (CT) scan of the liver during the surgery. All surgical instruments have trackable markers attached to them and a tracking camera sees these markers and can differentiate the different instruments from their attached markers. The achieved navigation accuracy with such a system was $4.5 \text{ mm} \pm 3.6 \text{ mm}$ averaged over nine surgeries [34]. Current research tries to compensate for deformations of the liver after the CT scan to the actual shape of the liver [12] [13].

2.2.1 Creation of preoperative 3D-models

[31] time consuming and method to create 3d-model from CT

2.2.2 Registration methods

Different registration methods exist. Discrete landmarks, surface scans and volumetric sonography scans are just a few of the approaches that can be used to achieve precise alignment of the preoperative image data with the surgical site [8].

2.2.3 Tracking modalities

To track surgical instruments and patient's anatomy (define the position and orientation in real time) during naviagated surgery a tracking system is needed. Tracking can be done by different technologies. The most used tracking modality is optical tracking.

Optical tracking

Optical tracking is the most used tracking modality in naviagated liver surgeries. Passive markers (spherical, retro-reflective that reflect infrared light) or active markers (infrared-emitting markers that are activated by an electrical signal) [39] are attached to the objects that need to be tracked. A tracking camera is then emitting infrared light by illuminators on the position sensor (only for passive markers). The position sensor determines the position and orientation of the tracked instruments based on the information it receives from those markers [1].

2.3 Surface reconstruction of unorganized points

A surface reconstruction's goal is to create a surface from sampling points. Two main steps need to be processed. First, collecting the sample points. Second, apply a reconstruction algorithm to the sampled points.

2.3.1 Data acquisition

There exist different methods of collecting surface points [16][25][14][11][15]. Optical (non-contact scan) scans are the most popular ones. Specialy laser based scanners can scan very fast and with a precision in the order of micrometers. Also contact scans exist [32]. Contact scans can also be very precise (in the order of micrometers). Only a few articles were published in the field of liver surface scanning [29] [37]. They used stereo laparoscopic cameras to sample the surface. The resulting sampling points lie on or near an unknown surface. A reconstruction algorithm has now to reconstruct the surface from these points.

2.3.2 Reconstruction algorithms

Again, a lot of reconstruction algorithms exist [27], but not all of them are made to reconstruct from unorganized points. This means that the point orders, orientations, connections and the topological type of the surface is not known a priori. Therefore it is necessary that the algorithm does not assume any structure on the data points [19] [40]. The orientations, connections and the topological type must be inferred from the points. This is a major difficulty of the general surface reconstruction problem [18]. In the past few decades, many algorithms that can solve this problem have been published. Nevertheless it is still a chal-langing task that is part of current research [26]. The available reconstrction types can be classified into two groups: implicit volume-based and explicit mesh-based reconstructions.

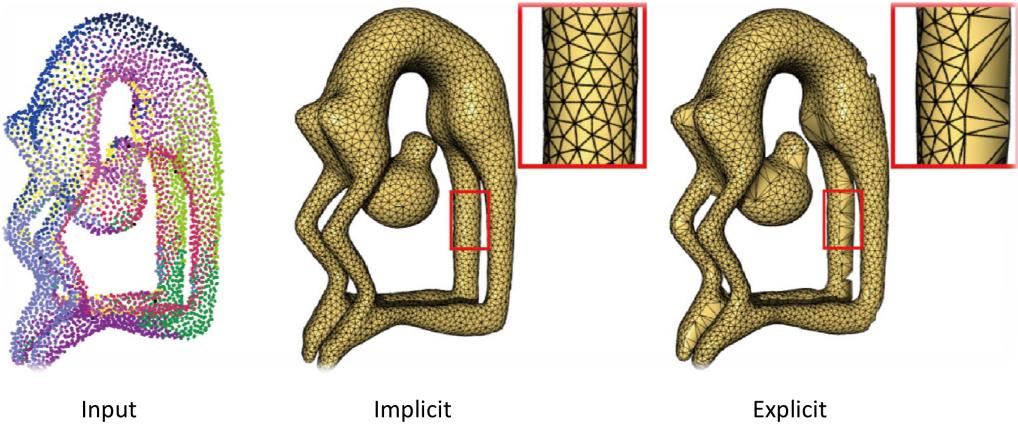


Figure 2.2. The difference between implicit and explicit surface reconstructions. On the left side is the pointcloud used as input. In the middle the result of an implicit reconstruction. On the right side the result of an explicit reconstruction [2]

Explicit mesh-based reconstruction

Explicit mesh-based reconstruction methods form a triangular mesh directly from the unorganized points. These mesh-based reconstructions are precise but they have problems with noise, complex shapes and especially holes in data.

Implicit volume-based reconstruction

Implicit volume-based reconstruction techniques construct an implicit volume-function from the input points. From the iso-surface of the volume-function a restored surface can then be obtained. For these methods it is not a problem if the surface topology is complex. But most of these methods suffer from oversmoothing the data and the need of accurate directions of normal vectors in addition to the unorganized points.

[20] oriented point set hornung2006robust [19] non uniformly sampled point clouds without normal information [40] NN to reconstruct from unorganized points

Chapter 3

Problem Statement

To make computer assisted navigation in liver resection surgeries more accessible to liver surgeons, a new concept has to be developed in order to do some first testings. Specifically, the method should fulfill the following:

- The software should guide the surgeon through the surgical procedure.
- A 3D-model of the liver should be created during the surgery.
- The planning for the resection of the tumor should be done intraoperatively on the created 3D-model.
- The method should be ready for testings in the OR.

Chapter 4

Concept

In this chapter the developed concept will be presented.

4.1 System

The hardware used with this system consists of:

- a tracked ultrasound device
- a tracked pointer tool
- an optical tracking camera to track the instruments
- a computer to run the software
- a 3D-monitor which displays the 3D contents of the software
- a touch-screen on a 2D-monitor to operate the software and show the ultrasound images

The software in this system consists of:

- a sampling method to collect points on the liver-surface
- a reconstruction method to reconstruct the surface from the sampled points
- a segmentation method to segment the tumors on the ultrasound images
- a planning method to plan the resection of the liver
- a navigation mode used to navigate during the removal of the tumor

4.2 Functionalities

4.2.1 Surface Reconstruction

4.2.2 Tumor Segmentation

(Automatic 3D)

4.2.3 Resection Planning

4.3 Workflow

4.3.1 Resection planning for non-anatomical ...

Chapter 5

Implementation

This chapter

5.1 Surface Reconstruction

5.1.1 Surface contact detection

5.1.2 Outlier removal

5.1.3 Reconstruction Parameters

grid search

5.2 Tumor Segmentation

graph cuts initialization method

5.3 Resection Planning

5.3.1 Cone fitting around tumor

5.4 Visualization for navigation

5.4.1 Ultrasound overlay

5.4.2 3D model

5.5 UI Concept

Chapter 6

Experiments

In this chapter experiments will be presented.

6.1 Surface Accuracy on a technical phantom

The work presented in this section was presented at CURAC, Luca

Surgical resection is the gold standard for curative care for primary and secondary hepatic tumors. This procedure usually involves removing the segment of the liver where the tumor is located. In this treatment, it is important to spare enough healthy parenchyma to preserve the function of the liver after surgery. Therefore, non-anatomical resection approaches are becoming more popular, as they try to spare as much healthy tissue as possible. This way, only the tumor and a safety margin of 5 – 10 mm are removed which allows multiple resections and re-treatments in case of recurrence [4]. However, especially in these non-anatomical resections, maintaining the safety margin is challenging as the tumor is removed by cutting around the tumor in a conical or wedge shape rather than a plane along anatomical landmarks. Therefore, image-guidance systems have been introduced to guide the surgeon to precisely follow a planned resection path. These systems rely on tracking devices (optical or electromagnetic) to measure the pose of the surgical instruments and use a registration process to align a preoperative model with the patient intraoperatively [23][8]. However, the setup and use of such systems is time consuming, complex and requires extensive training, which is a major reason why they are not widely used [21]. Additionally, the registration process introduces errors due to organ deformation between the image acquisition and the surgery. During conventional, non-anatomical resections a resection plan is drawn onto the liver before the start of the resection. Therefore, an important part of the resection plan is an accurate reconstruction of the liver surface. This surface is then used to project the outline of the tumor and a safety margin onto the surface. This is where the surgeon would start with the transection of the parenchyma. Previous work used such surface reconstructions based on laser scanners [35] for intraoperative registration, which requires additional equipment. In this study, we evaluated an ultrasound (US) based method to automatically reconstruct the liver surface intraoperatively.

6.1.1 Methodology

The image processing pipeline consists of three steps, the acquisition, the contact detection and the surface reconstruction (Figure 6.1). First the data from an ultrasound scanner (Flex focus 800, BK Medical, Denmark) and a tracking camera (Polaris, NDI, Canada) is

acquired and fused on a navigation system (CAS-One Vario, CAScination AG, Switzerland) for liver surgery. Then each image is classified whether it has contact to the liver surface or not. The position of the images with contact to the liver surface are then further processed in the surface reconstruction step to create a model of the liver surface. The result is then visualized in a 3D viewer.

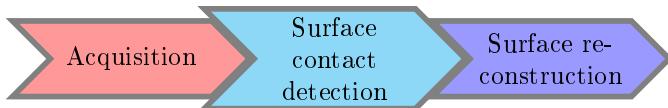


Figure 6.1. The data processing pipeline

Acquisition

During the data acquisition phase, the ultrasound image and the corresponding 6D pose are recorded using the navigation system. The ultrasound was calibrated using a Z-wire phantom [33] and is tracked by an optical tracking system. To simulate a liver surgery, a multimodal liver phantom (Figure 6.2) and an intraoperative ultrasound was used to get the ultrasound images. During the simulation the ultrasound device had a trackable and calibrated marker attached. To find an optimal sampling method, the liver was scanned with six different techniques (Figure 6.3). The two spiral techniques represent recordings of moving the US device to draw a spiral onto the liver. Either from the center to the peripheral part (spiral out) or vice versa (spiral in). The two sweep techniques represent recordings of moving the US device left and right (Sweep LR) or forward and backward (Sweep FB). The flower technique represents a recording of moving the US-device to draw a flower onto the liver. Additionally, a point grid was acquired as reference points for evaluation of the other reconstructions.



Figure 6.2. The US liver phantom used for the experiments in this study

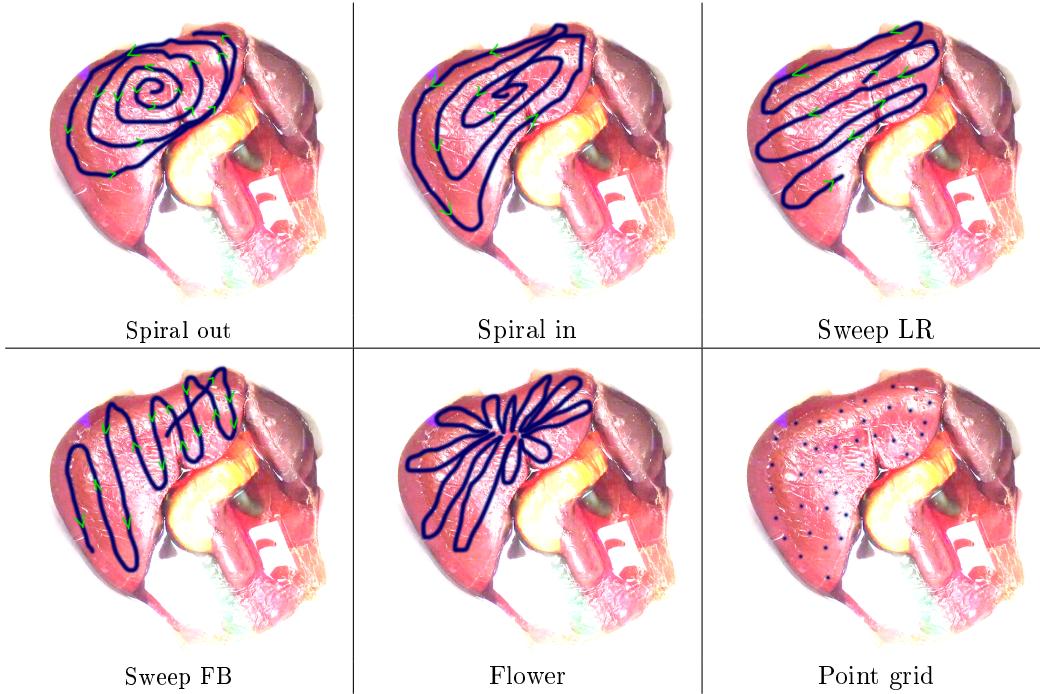


Figure 6.3. Different sampling movements of the ultrasound device over the surface of the liver

Surface contact detection

In the surface contact detection step, a classifier detects whether the US probe has contact to the liver or not. Therefore, a support vector machine (SVM) was trained with US images from the phantom and from previous navigated liver surgeries. The SVM was trained to classify the image into “no surface contact” (left) and “surface contact” (middle and right). The images were labelled as “surface contact” if at least 50% and the center had contact to the surface (Figure 6.4 middle). The classifier takes into account that US waves are reflected at the US probe-air interface when the US probe has no contact to the liver and therefore no image is formed. The features for the classifier were: mean, median, minimum, maximum, variance, skewness and kurtosis of the pixel values. All features are calculated on the upper half of the image. For training, a set of 2'311 images (1'056 with contact, 1'255 without contact) were used. The training data was composed of images from a phantom (88%) and images from previous navigated liver surgeries (12%). All computations were performed using the SciPy software package.

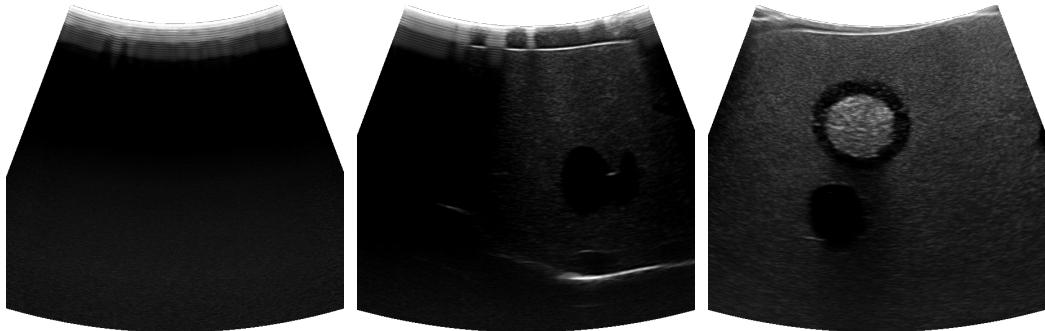


Figure 6.4. Three ultrasound images from left to right: No contact with the liver, difficult to decide (In this case it would be contact because the middle part of the image shows contact), contact with the liver

Surface reconstruction

To reconstruct the surface of the liver from the sampled points, the surface reconstruction algorithm by Hoppe et al. [18] was used. The algorithm consists of three phases. From an unorganized set of points, phase 1 constructs an initial dense mesh. Starting with the dense mesh created in phase 1, phase 2 reduces the number of faces and improves the fit to the data points. In phase 3, the surface representation is changed from a piecewise linear one (meshes) to a piecewise smooth one. For the computations the implementation in VTK (SurfaceReconstructionFilter) was used (neighborhood size of 50 and sample spacing of 10). Due to the different latencies of the US and the tracking system (with the US being slower), a delay of 4 frames (0.2 seconds) is applied to the tracking data.

Experimental evaluation

For evaluation of the surface detector the data was split into training (80%) and test data (20%). The precision and recall were calculated for performance analysis on the test set. To quantitatively evaluate the reconstructed surfaces, the points of the point grid measurement (414 points) were used as a reference. These reference points represent points on the surface of the liver in an undeformed state. For each of these reference points, the error is computed as the shortest distance to the reconstructed surface. All computations were performed using SciPy.

6.1.2 Results

Overall, the surface contact detector was evaluated on a test set with 2414 images. Additionally, 10 scans of the liver surface were evaluated against the reference points to measure the accuracy of the surface reconstruction.

Surface contact detection

To evaluate the contact detector, a test set of 2414 images with 50% contact and 50% no contact was used. The detector has a sensitivity of 0.95 and a specificity of 0.98. Out of all negative samples, 1.9% were detected as having contact. The prediction of one image takes 15 ms where most of the time (approx. 99%) is spent for feature extraction.

Surface reconstruction

Visual assessment

The reconstruction of the liver surface created lead to a smoothed version of the measured surface part. The measured surface corresponds to the surface of the liver (Figure 6.2). However, the reconstructed surface area is larger than the sampled part of the surface. This is a property of the algorithm, as it estimates a rectangular grid.

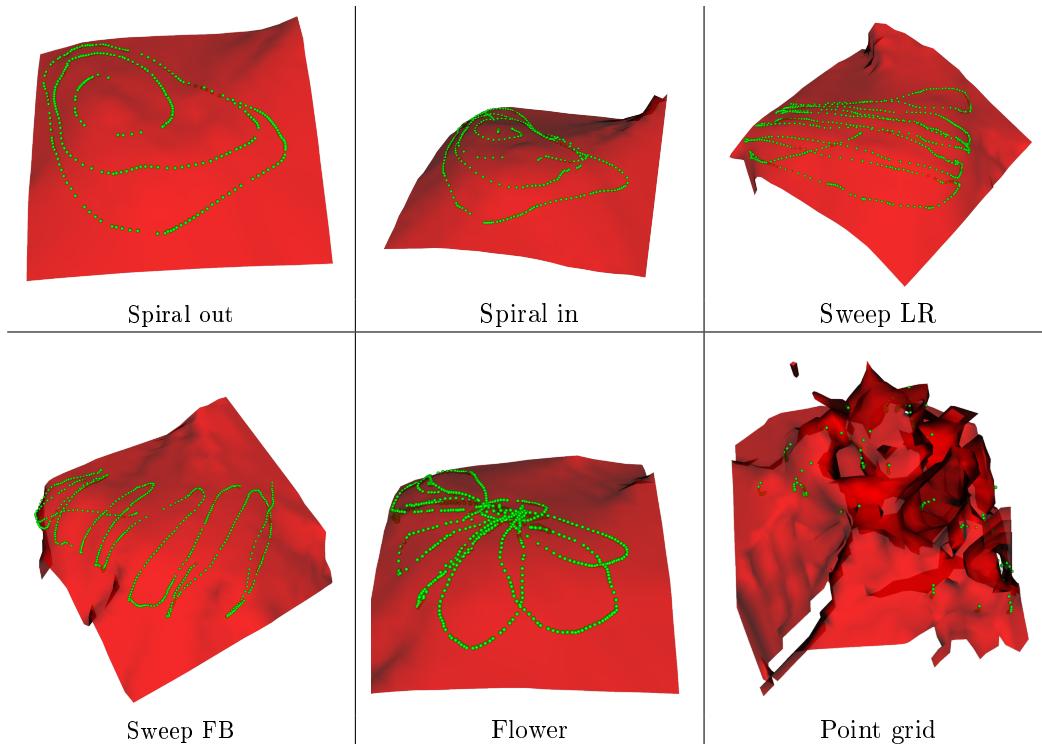


Figure 6.5. Reconstructed surfaces from different movements of the ultrasound device over the surface of the liver model. The names correspond to the movement drawings in figure 6.3

Quantitative analysis

To evaluate the accuracy of the reconstructed surfaces, the shortest distance of the reference points to the surface were computed. The overall median error for all the measurements is 2,5mm with an interquartile range of 1 mm – 5 mm. By projecting these errors corresponding to each reference point onto the liver surface, one can see that the highest errors are in segments 2 and 3 And the lowest in segments 4, 5, 6 and 8 (Figure 6.6).

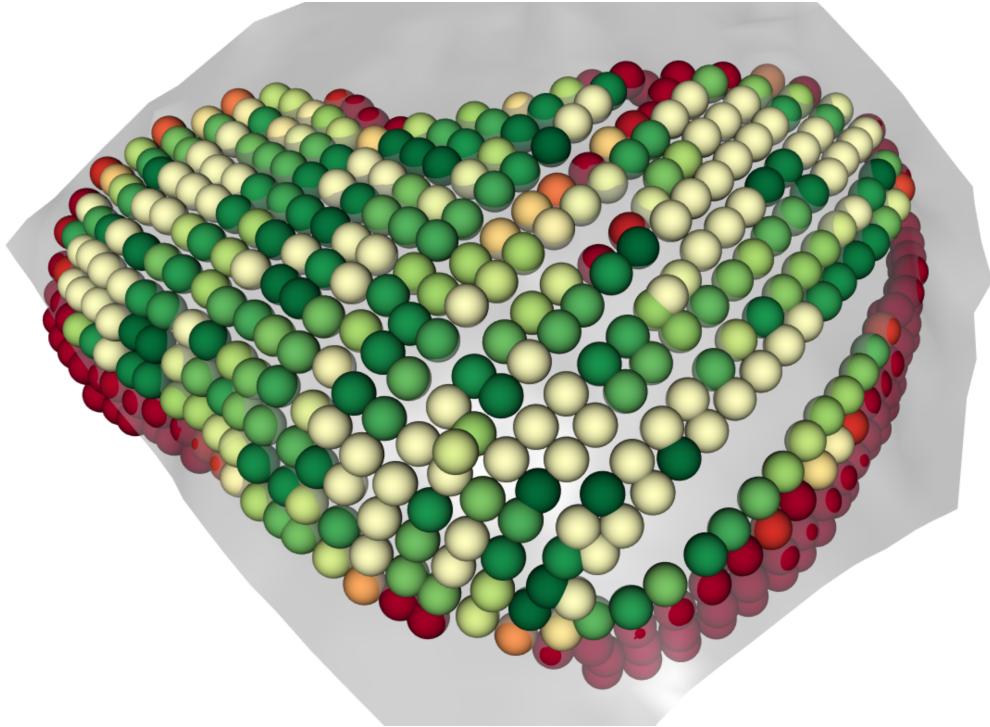


Figure 6.6. The mean distance of each reference point visualized by colors. All points with a mean distance of over 5 mm to the surface are colored dark red. Points with a mean distance below 1.5 mm are colored dark green.

6.1.3 Discussion

The surface contact detector is correctly classifying in 96% of the cases, with a very low false positive rate of 1.9%. This is especially important, as false positives lead to artifacts in the reconstructed surface. Furthermore, the processing time of 15 ms per image makes it suitable for real-time processing of the images as the ultrasound scanner runs at 20 Hz (50 ms / frame). When the US probe is removed from the liver surface there are 3-5 images which are wrongly classified as having a signal. This would cause artifacts in the surface reconstruction, and therefore they are filtered out later for surface reconstruction. This is mainly, because of the latency of the US scanner itself compared to the tracking system. The images are slightly blurrier (Figure 6.7), but from the tracking positions one can clearly see that they are not on the surface.

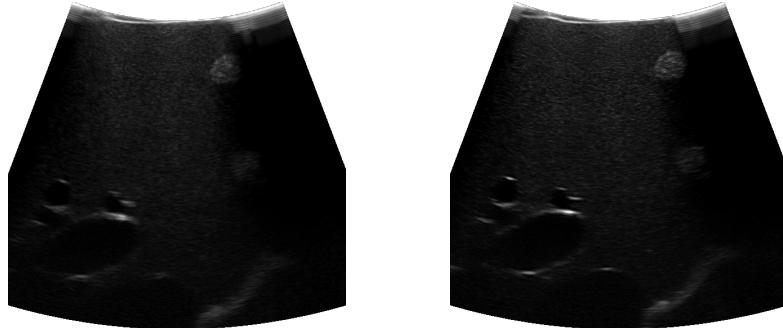


Figure 6.7. Wrong and correct classified images at the end of the measurement

Surface reconstruction

From a visual point of view the reconstructed surfaces of the US liver phantom look similar to the surface of the liver model. However, the spiral and the flower movement, led to a more accurate reconstruction.

From a quantitative point of view, it turned out that the largest average errors are in segment 2 and 3. This is likely because these liver segments are the softest on the phantom used for the measurements. Due to that, this segment was pressed down during the measurement which lead to a surface with a large distance to the reference points. Additionally, one can see that the average distance at the boundary of the liver is large as well. This could be because the US device was held between the wall of the tank and the liver model. Because of the small space between the wall and the liver, the pressure applied on the liver was larger than in other areas and the consequent distance between the reference points and the deformed surface became larger. However, this might also be the case in a clinical setting, as these regions are more difficult to reach with the US probe. Overall, the best accuracy, could be achieved in segments 4,5,6 and 8, which were the easiest to access in this setup. In a next step, this would also be analyzed on the human liver, to see in which segments this technique can be applied accurately.

To conclude, we presented a surface reconstruction technique, which can be used to intraoperatively acquire a surface model of the liver using navigated US. This can then be further used for intraoperative resection planning or surface-based registration.

6.2 Surface reconstruction on retrospective data

6.2.1 Methodology

Retrospective data from Banz et. al

6.2.2 Results

6.2.3 Discussion

6.3 Usability Test

3 surgeons questionnaire surface accuracy (using surface registration)

6.3.1 Methodology

6.3.2 Results

6.3.3 Discussion

Chapter 7

Discussion and Conclusions

7.1 Discussion

Interpret your results in the context of past and current studies and literature on the same topic. Attempt to explain inconsistencies or contrasting opinion. Highlight the novelty of your work. Objectively discuss the limitations.

7.2 Conclusions

Formulate clear conclusions which are supported by your research results.

Chapter 8

Outlook

Provide a vision of possible future work to continue and extend your thesis research.

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Appendices

Appendix A

Vector and Tensor Mathematics

A.1 Introduction

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A.2 Variable Types

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Appendix B

Another Appendix

B.1 Section 1

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B.2 Section 2

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