Workspace optimization for a surgical robot for liver tumor ablation

Nalet Meinen

Introduction

Liver cancer is the sixth most common cancer worldwide [1]. A common form of therapy against unresectable liver tumors is ablation. These ablation devices are destroying the tumor *in situ* by exposing the tumors to heat. The needle delivers this heat from the ablation device with radiofrequency or microwaves. It is one of the fewer less invasive procedures, compared to resecting liver tumors in a traditional manner. Recently, robotic systems have been introduced to assist in this procedure.

Such ablation methods are to plan by experienced surgical personnel. The medical professional need to create the trajectories before the operation. The ablation needle inserts in the trajectory. With no means to harm any critical blood vessels or other organs at risk. There are already computer-assisted planning systems which help to create those trajectories. However, for fully robotic ablations, an automatic trajectory planning system is needed. For efficiency in medicine and safety reasons, a robotic surgical system must do the ablation of a liver tumor. Furthermore, such a trajectory planning system should also be able to specify the optimal placement of the robot.

We hypothesize that it is possible to create a surgical planning system that also considers the workspace of a robot. The novel constraint-based planning system will test against segmented medical data [2]. Therefore, we aim to develop a trajectory planning system which optimizes the trajectories for a small required workspace, which also recommends an optimal setup of the robot.

Methodology

The surgical planning system plan the ablation of liver tumors for a robotic system and not for a procedure executed by a medical professional. For the robotic system, additional constraints about the workspace of the robot are part of the constraint problem.

Constraints

A paper from the University of Beijing [3] has already created a planning approach for usage by humans. These constraints fulfill the base of the problem:

H1: The needle trajectory should avoid critical structures, including the heart, lung, stomach, spleen, kidney, rib, spine, and vessel.

H2: The length of the needle trajectory l should be less than that of the ablation needle.

S1: Considering trajectories that point in the same direction for a compact workspace.

As there are already systems for optimal trajectory planning, therefore these simple constraints are enough for the planning part. The main goal is that all trajectories fit a compact workspace of a surgical robot.

Preparations

The segmented data contain only a hard constraint layer and a layer with tumors. Therefore, all layers, including the heart, lung, stomach, spleen, kidney, rib, spine, and vessel, will act as one layer. The algorithm will then run an intersect analysis against this so-called hard constraint layer to check if a trajectory conflicts with a vital organ.

Algorithm

The algorithm describes the steps from the preparation of the segmented layers until the presentation of the propagated workspace.

Figure 1 Steps of the algorithm

The algorithm starts with loading the pre-segmented files. Therefore, layers are created, giving later access to specific organs. The algorithm continues with the extraction of the tumor centroids. For every centroid of every tumor, we generate a sphere with the radius of the ablation needle. On the surface of the sphere, the algorithm distributes points evenly. These points then give us the trajectory vectors. From the trajectory vector, a 3d ablation object is now available. Every generated trajectory is a candidate that is run against the hard constraint layer as described in preparations. If the intersection test is successful, we remove the trajectory from the candidate's list. The results of the intersection test are all trajectories that are not intersecting with vital organs. For speed improvements, the intersection test is firstly run against the skin layer. This layer consists of fever points compared to the hard constraint layer.

The current candidate's trajectories are not violating any hard constraints. However, only so many trajectories can be used as there are tumors. The optimization part of the algorithm calculates the sum of all trajectory’s vectors. The algorithm allows a custom vector as input instead of the sum vector. The cosine similarity allows us to determine the most similar trajectory compared to the sum vector. For every tumor, the trajectory with the most similarity will remain as a final candidate.

The previous intersection test has already revealed the cross point between the trajectory and the skin. Using these points and adding the vector of the ablation needle is giving us the boundary points of the robotic workspace. A calculation of the workspace is now possible. The convex hull method allows us to extract the volume of a possible workspace in this final step.

Analysis

The program exports the volume of the robotic workspace and the number of tumors of the patient's data. Qualitative analysis is available through the 3d scene output. A set of 20 CT data will support the test case.

Results

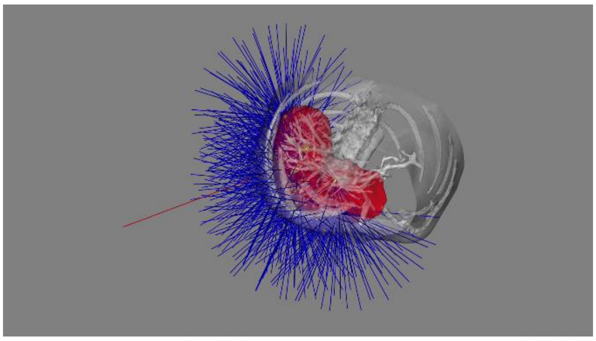

Figure 2 All generated trajectories with sum vector

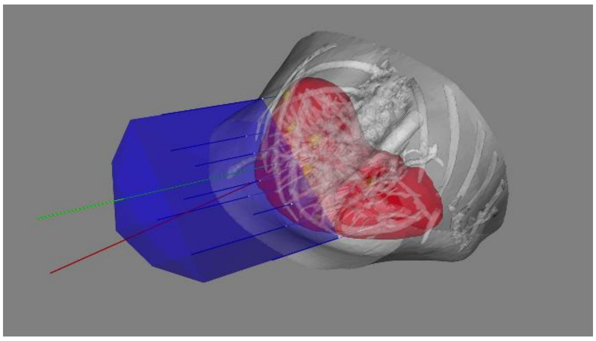

Figure 3 Final result of optimized robotic workspace

The output of the program divides in the subsection's constraints, algorithm, and statistics. Were constraints would show the output of the trajectory planning, the algorithm part the workspace of the robot, and the statistics will analyze the workspaces.

Constraints

The first part of the algorithm generates the trajectory planning. The output of the planned trajectories is good enough for further analysis. The created trajectories may still have some intersection with vital organs. The intersection errors are due to the implementation with the VTK library [4]. Optimizing that would need some further research.

Figure 1 shows many candidates for further analysis for test data with seven tumors.

Algorithm

The result of the created workspaces in figure 2 is an optimized workspace. The workspace is tiny. The workspace is, in most cases, easily accessible. We assume that there should be fewer problems with placing the camera and the surgical robot for the ablation procedure.

The algorithm allows the optimization against a custom set vector. Also, these results are quite good and show similar results to the calculated sum vector.

Statistics

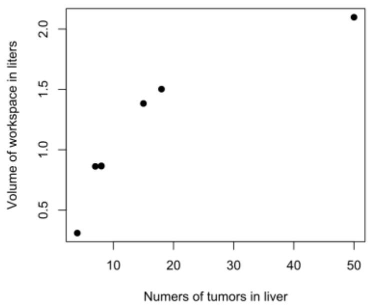

Figure 4 Scatterplot of found tumors concerning workspace size

Figure 4 shows seven patient data containing more than one tumor. Calculation a convex hull requires more than two trajectories. Having two trajectories leads to 4 points, which is a surface rather than a volume. The table shows that the growth of the volume corresponds with the number of tumors. A reasonable estimate of the correspondence of the number of tumors and workspace size is not possible with such a small data set.

Discussion

In the first version of this report, the topic would be a trajectory planning system for surgical robots. While there have been other works about this [5], we aimed to optimize the trajectories for a compact workspace. Segmented data of good quality is mandatory for such an experiment. The roughly implemented trajectory planning led to satisfactory results. Using the vector sum led to optimal trajectories which have some distance from the vital organs.

The direction of the workspace tends to point away from the liver to the left. The algorithm did not intend this, but useful trajectories are also accessible from the side of the liver. So, the sum of vectors would always tend in this direction. From a qualitative view, the planned workspaces are suitable, because there are small and easily accessible for a robot and the computer-assisted navigation system.

The algorithm does not segment the tumors in different ablation section. Better results are achievable with breaking large tumors into smaller ablation sections. More ablation points would have an impact on the workspace, as seen in the statistics part of the results. The sample size is small because only few image data contained multiple tumors to calculate a volume.

Combining more soft constraints like distance from vital organs can improve the trajectories. Also, calculating an invasiveness score could be significant for a procedure. For the hard constraint part, the needle should pass the surface of the needle with an angle to the surface of less than 20°. This hard constraint would give an even better view of the planned trajectories. However, not considering this hard constraint gave already a steady data output.

To conclude, this project has shown that it is achievable to choose trajectories suitable for patient and robot. It is possible to take the constraints from the robot into account and generate a functional and small workspace for a robot. With this newly gained knowledge, an ablation robot can work with a workspace of only a few liters.

Acknowledgments

The author wants to thank for the University of Bern and the ARTORG Center for Biomedical Engineering Research. Special thanks go to Iwan Paolucci for the help, support, and believing in the success of this experiment.

References

1. Miller KD, Nogueira L, Mariotto AB, et al (2019) Cancer treatment and survivorship statistics, 2019. CA Cancer J Clin. https://doi.org/10.3322/caac.21565
2. IRCAD - Hôpitaux Universitaires 3D-IRCADb 01. https://www.ircad.fr/research/3d-ircadb-01/
3. Zhang R, Wu S, Wu W, et al (2019) Computer-assisted needle trajectory planning and mathematical modeling for liver tumor thermal ablation: A review. Math Biosci Eng 16:4846–4872. https://doi.org/10.3934/mbe.2019244
4. Lorensen B, Schroeder W, Martin K (2016) VTK - The Visualization Toolkit. In: Open Source
5. Liu S, Xia Z, Liu J, et al (2016) Automatic Multiple-Needle Surgical Planning of Robotic-Assisted Microwave Coagulation in Large Liver Tumor Therapy. PLoS One 11:e0149482. https://doi.org/10.1371/journal.pone.0149482