Use of stereo-laparoscopic liver surface reconstruction to compensate for pneumoperitoneum deformation through biomechanical modeling.

Andrea Teatini, Jean-Nicolas Brunet, Sergei Nikolaev, Bjørn Edwin, Stéphane Cotin, Ole Jakob Elle

To cite this version:

Andrea Teatini, Jean-Nicolas Brunet, Sergei Nikolaev, Bjørn Edwin, Stéphane Cotin, et al.. Use of stereo-laparoscopic liver surface reconstruction to compensate for pneumoperitoneum deformation through biomechanical modeling.. VPH2020 - Virtual Physiological Human, Aug 2020, Paris, France. hal-03130613

HAL Id: hal-03130613

https://hal.inria.fr/hal-03130613

Submitted on 3 Feb 2021

Use of stereo-laparoscopic liver surface reconstruction to compensate for pneumoperitoneum deformation through biomechanical modeling.

Teatini A.[a,b*], Brunet J.N.[f,+†], Nikolaev S.[f,+], Wang C.[a,e], Edwin B.[a,c,d], Cotin S.[f], Elle O.J.[a,b]

[a] *The Intervention Centre, Oslo University Hospital Rikshospitalet, Oslo, Norway.*

[b] *Department of Informatics, University of Oslo, Oslo, Norway.* [c] *Institute of Clinical Medicine, University of Oslo, Oslo, Norway.* [d] *Department of Hepato-Pancreatic-Biliary surgery, Oslo University Hospital, Oslo, Norway.* [e] *Norwegian Colour and Visual Computing Lab, Norwegian University of Science and Technology, Gjøvik, Norway.* [f] *Mimesis team, INRIA, Strasbourg, France.*

Keywords Image-guided surgery, surgical navigation, computer vision, biomechanical modeling.

1. Introduction

Abdominal organs undergo large deformations due to intra-abdominal pressure (pneumoperitoneum) during laparoscopic surgery, especially large organs such as the liver [2]. These deformations cause large inaccuracies when using surgical navigation systems [2]. Fortunately, intra-operative imaging through CT/MRI can be acquired in modern hybrid ORs as well as laparoscopic ultrasound and can both be used to provide an updated organ models. However, these medical imaging modalities are expensive and may extend the surgical workflow, hence, biomechanical models could be used as a solution for intra-operative registration, also to account for organ deformations due to surgical manipulation. Within this study, we propose a solution to compensate for pneumoperitoneum, which could greatly increase the accuracy of liver surgical navigation systems.

2. Methods

The method presented in this study incorporates multiple technologies: optical tracking, camera and hand-eye calibration, point-based registration, stereo camera reconstruction and biomechanical modeling.

2.1 Dataset acquisition

Three trials on porcine models, with weight ranging from 59.5 to 70 kg, were included in this study. A Hybrid OR, equipped with a SIEMENS SOMATOM CT scanner was used to perform laparoscopic liver resection surgery and acquire medical images directly on the operating table. To simulate current clinical scenarios, images were acquired (with tube disconnect to remove artifacts due to breathing) both pre-operatively (without pneumoperitoneum) and intra-operatively (after pneumoperitoneum, set at 13 mmHg). Segmentation of both liver parenchyma and veins (Figure 1) was conducted semi-automatically using ITK-SNAP followed by manual corrections applied in 3DSlicer and reconstructed into 3D models.

2.2 Stereo point cloud reconstruction and rigid registration

Surgical navigation was conducted using optical tracking, camera and hand-eye calibration were computed as described in [2] and stereo reconstruction was computed based on [3].

The surgeon performed a maneuver with the laparoscopic camera to acquire approximately 15 frames per dataset. These were reconstructed into point clouds and transformed into O coordinates according to: $T_I^C = (T_C^M)^{-1} \cdot (T_M^O)^{-1} \cdot T_P^O \cdot T_P^I$, which follows the diagram in Figure 1:

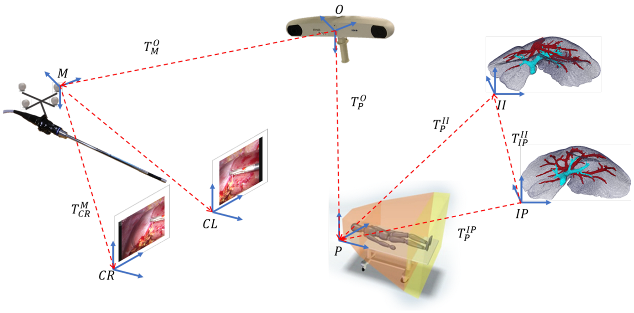

Figure 1: Transformation diagram for stereo reconstruction point clouds registered to the optical tracking system as global reference (O).

Where *C* can be used for either *CL* or *CR*, respectively left and right cameras, *M* markers on the laparoscope camera, *O* optical tracking system, *P* patient coordinates and *I* medical image coordinates (*IP* pre-operative *II* intra-operative imaging). Transformation T_{II}^{IP} was computed aligning the back of the liver, whereas transformation T_{II}^{O} was computed using 15 laparoscopic fiducials, which were sampled using a calibrate and tracked laparoscopic grasper.

2.3 From rigid to deformable registration

Most surgical navigation solutions available on the market rely on pre-operative rigid registration [1]. We propose to further extend the rigid registration by deforming a virtual biomechanical model built from the pre-operative segmentation until a part of its surface

---

[*] Corresponding author. Email: andre_tea@outlook.com

[†+] Denotes equal contribution and listed in alphabetical order matches the stereo reconstruction. We hypothesize that, given an accurate identification of the deformation using a reconstructed stereo point cloud, a physically-accurate simulation of the biomechanical model will yield the global deformed volumetric shape of the liver. In this work, a non-linear Neohookean homogeneous hyperelastic material was used. Starting from the initial rigid registration (T_{II}^{IP}), the point cloud of the stereo reconstruction was projected onto the pre-operative CT surface of the model using an additional iterative closest point registration. A displacement was imposed from the projected area of the undeformed model (pre-operative) to the intra-operative point cloud using a distance penalty force method. The deformed shape of the model was then solved using a finite element (FE) method. The process was repeated by projecting the point cloud onto the previous deformed solution until a minimum hyperelastic energy state was reached.

3. Results and Discussion

To evaluate the deformation, we annotated 15 vessel bifurcation intersections (in pre-operative and intra-operative) per trial. We conducted two biomechanical simulations: one using the stereo reconstructed point cloud (which includes computer vision inaccuracies and shows only a part of the liver visible through the camera), and a second using the full liver segmented point cloud from the intra-operative CT scan.

Vessel Bifurcation Evaluation						
		mean	median	min	max	std
Trial 4	Rigid	19.80	17.77	5.17	55.31	14.38
	Intra-op CT BM	11.25	11.33	1.16	33.19	7.54
	Stereo BM	22.66	22.79	6.53	34.84	7.24
Trial 5	Rigid	28.47	21.65	6.57	67.29	16.12
	Intra-op CT BM	19.75	20.38	9.55	37.91	8.01
	Stereo BM	27.35	26.97	9.14	57.40	14.61
Trial 6	Rigid	17.27	12.04	4.33	60.67	14.88
	Intra-op CT BM	10.38	8.47	1.53	23.08	6.19
	Stereo BM	26.56	24.75	15.96	43.32	7.40

Table 1: Results of the biomechanical (BM) simulations using the vessel bifurcation target registration errors, in [mm].

The results are summarised in Table 1. They show that the registration based on the full intra-operative segmented point cloud greatly improves the accuracy as compared to the rigid registration. However, the stereo camera reconstruction provides only some degree of improvement (similar means but with much lower standard deviation, indicating that the bifurcations are closer to each other). Most of this inaccuracy appears to be due to the back side of the liver (visible in Figure 2), which, in the stereo-reconstructed point cloud, cannot be reconstructed (not visible with the camera). In addition, to evaluate the accuracy of the stereo reconstructed point clouds, Hausdorff distances and *rms* to the respective intra-operative CT scan were computed for each trial. Averaged across the three trials, Hausdorff distances were 7.06±2.41 mm, and *rms* was 9.35±2.94 mm.

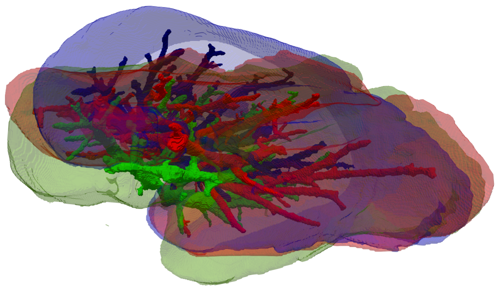

Figure 2: Example of resulting simulation using the stereo-reconstruction point cloud. Red is intra-operative CT, blue is the pre-operative CT and green is the resulting simulation.

4. Conclusion

In this paper we proposed a way to compensate for pneumoperitoneum deformation using stereoscopic point cloud reconstruction combined with non-rigid registration using biomechanical modeling. The results are two: firstly, the stereo reconstruction correctly reproduces the shape of the intra-operative liver (relatively low Hausdorff and *rms*, as well as accurate deformation of the liver top, as shown in Figure 2); secondly, the biomechanical model can compensate pneumoperitoneum, however, since the stereo reconstruction point cloud does not reproduce the back of the liver, the results are not accurate yet. In future works, we believe that boundary conditions will considerably improve the stereo-reconstruction-based simulation by compensating the erroneous deformation of the back of the liver (especially for humans, where the liver is more constrained). Moreover, using heterogeneous models which incorporate the blood vessels, we could be able to simulate pneumoperitoneum even more accurately.

Acknowledgements

This work was supported by H2020-MSCA-ITN Marie Skłodowska-Curie Actions, Innovative Training Networks (ITN)-H2020 MSCA ITN-2016 GA EU project number 722068 High Performance Soft Tissue Navigation (HiPerNav). The authors also thank the staff at Oslo University Hospital.

References

[1] Gian Andrea Prevost, Benjamin Eigl, Iwan Paolucci, Tobias Rudolph, Matthias Peterhans, Stefan Weber, Guido Beldi, Daniel Candinas, and Anja Lachenmayer. Efficiency, accuracy and clinical applicability of a new image-guided surgery system in 3d laparoscopic liver surgery. *Journal of Gastrointestinal Surgery*, pages 1–8, 2019.

[2] Andrea Teatini, Egidijus Pelanis, Davit L Aghayan, Rahul Prasanna Kumar, Rafael Palomar, Åsmund Avdem Fretland, Bjørn Edwin, and Ole Jakob Elle. The effect of intraoperative imaging on surgical navigation for laparoscopic liver resection surgery. *Scientific Reports*, 9(1):1–11, 2019.

[3] Congcong Wang, Faouzi Cheikh Alaya, Mounir Kaaniche, and Ole Jakob Elle. Liver surface reconstruction for image guided surgery. In *Medical Imaging 2018: Image-Guided Procedures, Robotic Interventions, and Modeling*, volume 10576, page 105762H. International Society for Optics and Photonics, 2018.