A fournir au format WORD exclusivement

Titre: Fast and stable Finite Element simulation for surgical assistance - application to augmented reality and robotic control.

Directeur(s) de Thèse : Courtecuisse, Hadrien (HDR, CNRS)

Unité(s) d'Accueil(s) : MLMS

Établissement de rattachement : ICube

Collaboration(s) (s'il y a lieu) :

Rattachement à un programme (s'il y a lieu) :

Résumé **(1500 caractères au maximum)** :

La réalité augmentée (RA) est de plus en plus utilisée en médecine, car offre la possibilité d'ajouter des informations supplémentaires (vaisseaux, tumeurs ...) au-dessus des images médicales en vue d'aider les chirurgiens lors de la procédure. Les méthodes par éléments finis (EF) sont parmi les plus efficaces pour effectuer le recalage non rigide nécessaire pour la RA. Cependant, en pratique, seule une vue partielle des organes est souvent disponible pendant l'opération. Or, du fait des déformations importantes, les solutions par EF sont soumises à des incertitudes. Afin de prendre des décisions médicales basées sur la RA, une mesure quantitative de l'incertitude doit être fournie au chirurgien en temps réel. Cette information est particulièrement nécessaire pour les structures internes profondes situées loin des données extraites des images.

Dans cette thèse, nous souhaitons développer des méthodes de simulation inverses afin de réaliser une étude mécanique permettant d'évaluer le domaine de mobilité du modèle EF tout en satisfaisant l'ensemble des contraintes utilisées pour le recalage. Cette étude devrait permettre de fournir des informations supplémentaires qui peuvent être utilisées pendant l'opération pour évaluer la fiabilité de la RA. Le but de cette thèse est de donner un indice de confiance du recalage sous forme de carte, permettant d'estimer la mobilité de chaque point du maillage et de montrer le lien avec l'incertitude.

Pour ce faire, nous souhaitons étudier l'influence des lois constitutives des modèles biomécaniques (notamment en utilisant des modèles hyperélastiques), les paramètres et les conditions limites. Il sera également nécessaire d'étudier la stabilité des modèles non linéaires pour ces applications de recalage. L'application envisagée concerne le recalage du foie pour les procédures percutanées sous fluoroscopie. Les résultats obtenus pourront alors être combinés à notre projet de robotique qui vise à automatiser le geste d'insertion d'aiguille avec l'aide de la robotique.

Fast and stable Finite Element simulation for surgical assistance

- application to augmented reality and robotic control -

Context: Radiofrequency ablation (RFA) is a percutaneous procedure that uses electrical energy and heat to destroy cancer cells. In this context, access to organs is ensured by using needles puncturing the skin, which represents the least invasive surgical technique to access deep internal structures into the organs. Unlike traditional (mini-) invasive approaches, the needles only affect a localized area close to the needle shaft, thus reducing the occurrence of traumas and risks of postoperative complications **[VLSP18]**. However, **needle-based approaches can be exceedingly complex**. Indeed, the effectiveness of needle-based intervention depends on the accuracy of the needle positioning (≈ 3 mm **[JBTM18]**). Reaching this accuracy is challenging because, contrary to laparoscopic surgery, no direct visual access is permitted.

Advanced numerical simulators are now considered a clinically relevant tool for students' training and formation. This is mainly because deformable models are simultaneously very realistic (both visually and physically) and very efficient to allow real-time computations, sometimes including validation of their behavior against real organs **[MHCW10]**. The general trend is to introduce biomechanical models directly in the Operating Room for visual assistance during the surgery providing an Augmented Reality (AR) view of internal structures. As opposed to image-to-image registration, biomechanical models can predict the behavior of structures. It can give a physics-based extrapolation of the deformation in areas where few or no intraoperative data are available (see **[PCRA17]** for a detailed discussion).

Most of the time, only a partial view of the organs is available intra-operatively. FE solutions are therefore subject to uncertainties during the non-rigid registration process. Therefore, quantitative measurement of uncertainty should be provided to the surgeon in real-time to make medical decisions based on augmented visualization. This information is especially needed for deep internal structures far from intraoperative image data.

We are particularly interested in the robotization of percutaneous procedures in the liver. Although this Ph.D. won't explicitly address the robotic aspects, it will be part of a larger autonomous robotic needle steering project for cancer treatments. In addition, thanks to our collaboration with the IHU Strasbourg, we aim at testing our methods during an animal experiment.

Objectives: In 2018, we introduced a registration method **[AGVM18]** successfully applied during an actual human intervention. However, this method is based on markers tracked with external infrared cameras, which is impossible in a percutaneous context since the abdominal cavity is not open. In this Ph.D., we will extend this method for needle insertion applications using fluoroscopy and fiducials markers (see **Fig.1**).

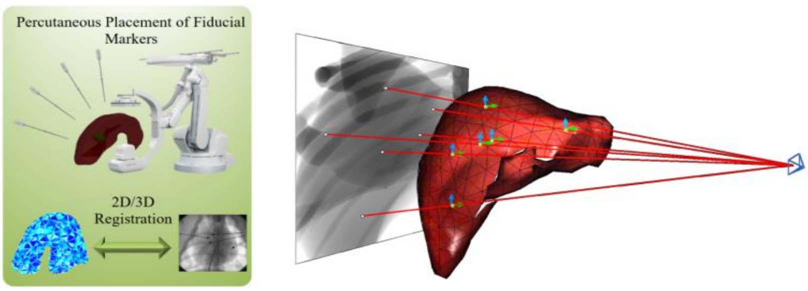
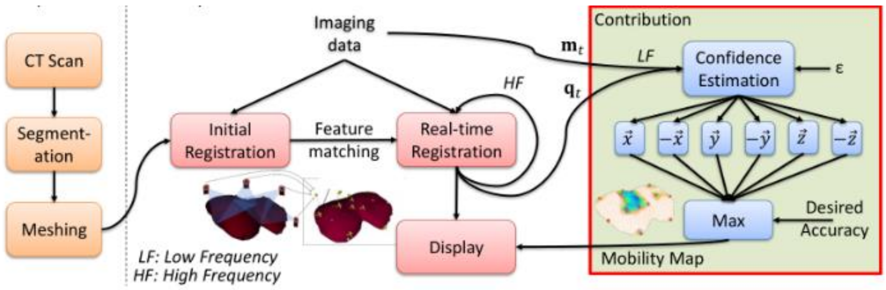


Figure 1: *(Left) Clinical workflow. (Right) Registration of a liver with virtual data. The imaging plane is represented along with the position of the radiating source (in blue), the internal marker's projections (black dots), and the resulting projection lines (red lines). To enforce registration, the 3D markers (green dots) are constrained on the projection lines*

We consider a set of gold fiducials manually placed percutaneously in the liver before the registration. A similar method has already been employed in **[OSMN16]** for radiotherapy of malignant liver tumors to guide the Cyberknife. Thanks to recent advances of Artis Zeego imagers, an initial volume image acquisition can be performed, providing 3D positions of fiducial at the initial step. During the breathing motion, fiducial markers are tracked with fluoroscopy, and the biomechanical model will be registered in real-time with 2D projective constraints. Therefore, the first objective of this work is to propose a 2D/3D registration procedure, using projective constraints, to perform the registration during the breathing motion.

Another critical challenge concerns the validation and the accuracy of the registration procedure. Indeed, markers being placed manually without any strong assumption on their location, some model parts may be subject to uncertainties. However, providing a quantitative measurement of the uncertainty is a significant obstacle to the actual usage of these numerical tools in the OR and, more importantly, for the automatic robotic needle insertion. In this Ph.D. We will develop a method for online measurement of a confidence map associated with the non-rigid registration of a biomechanical model **[BCCB19]**. The general workflow is illustrated in figure 4.



General workflow of the proposed solution. The method computes asynchronously a confidence map of the registered model applying forces on the registered configuration in various directions $\vec{x}, \vec{y}$ and $\vec{z}$ in order to estimate the mobility of the model

An augmented view combining the deformed model with medical images is displayed at high frequency. Asynchronously, at low frequency, image data and positions of the registered model are used as input of a mechanical study allowing evaluating the model's mobility. Finally, the confidence map can be used intraoperatively to only show the reliable parts of the numerical model in the augmented view. The mobility map is then combined with the augmented view of the organ only to display the reliable parts of the model fitting the desired accuracy for the surgical procedure.

The mobility is defined as the maximal displacement of the model subject to both an estimated force identified to prevent injury of tissues and image-based constraints used to perform the registration. The rationale behind this is to consider that image data provide ground truth positions of the markers. In contrast, other organ parts are subject to uncertainty, mainly related to unknown boundary conditions and mechanical parameters. We believe that mobility is directly related to the uncertainty of the registration and can be used to assess the solution's reliability. For this purpose, two key challenges will be studied i) to work with hyperelastic modeling and study the influence of the constitutive model both on the accuracy of the registration and the confidence evaluation, ii) to study the stability of the registration procedure with such nonlinear models.

The work will be organized as follows :

- State-of-the-art on simulations and augmented reality
- Development and integration in the SOFA framework
- Application of the method in different examples

Student profile:

- Technical Background: research skills, numerical resolution, FEM
- Coding skills: C++, Python, Git
- Soft skills: teamwork, autonomous

References

[**MHCW10**] S. Marchesseau, T. Heimann, S. Chatelin, R. Willinger, and H. Delingette, "Multiplicative Jacobian Energy Decomposition Method for Fast Porous Visco-Hyperelastic Soft Tissue Model," in *Lecture notes in computer science*, vol. 6361, Springer, 2010, pp. 235–242.

[**OSMN16**] K. Ohta, M. Shimohira, T. Murai, J. Nishimura, H. Iwata, H. Ogino, T. Hashizume, and Y. Shibamoto, "Percutaneous fiducial marker placement prior to stereotactic body radiotherapy for malignant liver tumors: An initial experience," *J. Radiat. Res.*, vol. 57, no. 2, pp. 174–177, 2016.

[**PCRA17**] I. Peterlik, H. Courtecuisse, R. Rohling, P. Abolmaesumi, C. Nguan, S. Cotin, and S. E. Salcudean, "Fast Elastic Registration of Soft Tissues under Large Deformations," *Med. Image Anal.*, 2017.

[**JBTM18**] T. L. De Jong, N. J. van de Berg, L. Tas, A. Moelker, J. Dankelman, and J. J. van den Dobbelsteen, "Needle placement errors: Do we need steerable needles in interventional radiology?," *Med. Devices Evid. Res.*, vol. 11, pp. 259–265, 2018.

[**AGVM18**] Y. Adagolodjo, N. Golse, E. Vibert, M. De Mathelin, S. S. Cotin, and H. Courtecuisse, "Marker-Based Registration for Large Deformations - Application to Open Liver Surgery," *Proc. - IEEE Int. Conf. Robot. Autom.*, vol. 6, pp. 4007–4012, 2018.

[**VLSP18**] L. Viganò, A. Laurenzi, L. Solbiati, F. Procopio, D. Cherqui, and G. Torzilli, "Open Liver Resection, Laparoscopic Liver Resection, and Percutaneous Thermal Ablation for Patients with Solitary Small Hepatocellular Carcinoma (≤30 mm): Review of the Literature and Proposal for a Therapeutic Strategy," *Dig. Surg.*, vol. 35, no. 4, pp. 359–371, Jul. 2018.

[**BCCB19**] P. Baksic, H. Courtecuisse, M. Chabanas, and B. Bayle, "FEM-based confidence assessment of non-rigid registration," in *Surgetica*, 2019, pp. 17–18.