

Combining Visual Cues with Interactions for 3D-2D Registration in Liver Laparoscopy

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Résumé

La réalité augmentée pour la cœlioscopie monoculaire du foie nécessite le recalage d'un modèle préopératoire 3D avec une image de cœlioscopie. La forme du modèle préopératoire du foie peut changer de manière significative par rapport à sa forme peropératoire inconnue, rendant le problème du recalage difficile. Le foie n'est que partiellement visible dans l'image de cœlioscopie ce qui accroît cette difficulté. Les approches précédentes sont soit manuelles, utilisant un modèle rigide, soit automatiques, reposant sur des repères visuels extraits de l'image et utilisant un modèle biomécanique. Nous proposons une nouvelle approche hybride qui combine le meilleur des deux abords. Les repères visuels nous permettent de capturer la perception de la scène tandis que les interactions utilisateur nous permettent de tirer parti des connaissances du chirurgien et de sa compréhension spatiale de l'anatomie du patient. Nous avons comparé notre méthode avec les précédentes en termes de précision et de répétabilité en utilisant un phantom et des données issues de patients.

Mots Clef

Cœlioscopie, foie, recalage, 3D-2D, réalité augmentée.

Abstract

Augmented Reality (AR) in monocular liver laparoscopy requires one to register a preoperative 3D liver model to a laparoscopy image. This is a difficult problem because the preoperative shape may significantly differ from the unknown intraoperative shape and the liver is only partially visible in the laparoscopy image. Previous approaches are either manual, using a rigid model, or automatic, using visual cues and a biomechanical model. We propose a new approach called the hybrid approach combining the best of both worlds. The visual cues allow us to capture the machine perception while user interaction allows us to take advantage of the surgeon's prior knowledge and spatial understanding of the patient anatomy. We compared our method to previous ones using phantom and patient data in terms of accuracy and repeatability.

Keywords

Laparoscopy, liver, registration, 3D-2D, augmented reality.

1 Introduction

One of the main current limitations of laparoscopy is the difficulty to accurately localize the target organ's internal anatomy, owing to the absence of tactile feedback. This is a particularly important issue for the liver, which may contain malignant tumours to be precisely resected with an oncologic margin. Augmented Reality (AR) is a promising approach to overcome this limitation. The key idea is to overlay information extracted from a preoperative CT or MR volume onto the laparoscopy images. These information may be the tumours and their oncologic margin but also the vascular structure. Technically, this requires one to align or *register* the preoperative volume to the laparoscopy image. This is a very challenging and currently highly researched problem. The difficulty is two-fold. First, the liver is only partially visible in the laparoscopy image due to its large size and proximity to the laparoscope. Second, the liver deforms substantially between the preoperative volume and the laparoscopy image due to the pneumoperitoneum (the intra-operative gas insufflation) and its manipulation by the surgical instruments. We focus on regular laparoscopy, which in terms of computer vision is a single monocular pin-hole camera, and forms the standard in operating theatres. It is obvious that any system designed for monocular laparoscopy extends to stereo-laparoscopy.

Currently, the most promising registration approaches share two main features. First, they solve the registration from the image contents only, without resorting to external hardware. Second, they use a *preoperative 3D model* consisting of the liver, tumours and vessels surface reconstructed by segmenting the preoperative volume. From these, the state-of-the-art registration methods are either *manual* [15] or *automatic* [1, 2, 8]. In [15], the preoperative 3D model is rigidly registered to the laparoscopy image by means of user interaction. In [1, 2, 8], the preoperative model is deformed following a biomechanical model via an ICP-like procedure to fit visual cues extracted from the laparoscopy image. These visual cues are anatomical landmarks including the falciform ligament and the inferior

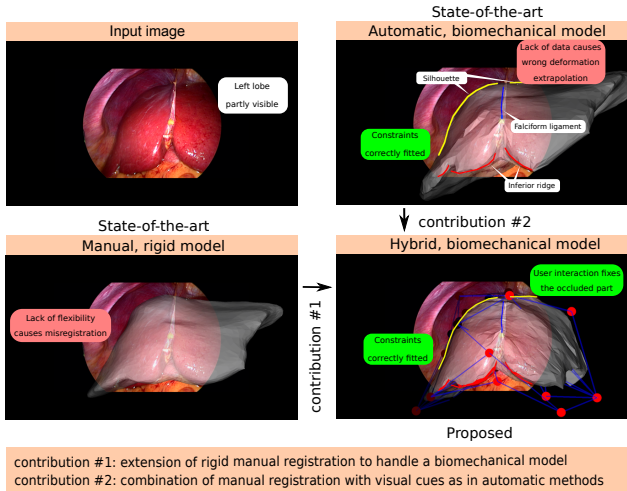


Figure 1 – Registration results delivered by the state-of-the-art methods and the proposed one. (top left) The input laparoscopic image. (top right) Results from the automatic method [2] based on visual cues (the contour constraints in yellow, blue and red). (bottom left) Results of the manual rigid registration method [15]. (bottom right) Results of the proposed hybrid method, combining visual cues with a biomechanical model through cage-based tactile interaction. The cage’s control points (red dots) are used to edit the registration simultaneously with an automatic optimization procedure exploiting the visual cues.

ridge, and the silhouette. The current manual and automatic approaches both present important shortcomings, illustrated in figure 1. In [15], the rigidity assumption is far too restrictive to accurately model the liver deformation. In [1, 2, 8], the visual cues are sparse and do not convey enough information to unambiguously constrain registration. Though the reasons are different, this results in both cases in misregistration, impairing the reliability of AR.

We propose an *hybrid* registration approach. The key idea is that the manual and automatic approaches are highly complementary. Our hybrid approach extends and draws on the strengths of both by combining user interaction with visual cues and a biomechanical model. In other words, the rationale is that both the machine and the user perception are valuable and should be taken into account via the visual cues and interaction respectively. In the presence of both user interaction and visual cues, our hybrid approach bundles all constraints in a single registration. In the absence of user interaction, it behaves similarly to the existing automatic approaches. In the absence of visual cues, it allows the user to edit the registration under guidance of the biomechanical model. This is a significant improvement compared to the existing manual approach as it allows the user to fully express their expertise in anatomy, prior experience and spatial understanding of the case at hand to the system. We have implemented this idea following the cage-based paradigm from the field of shape editing. The cage may be seen as a set of draggable control points enclosing

the organ. Shape editing is a widely studied problem, to which the main proposed approaches are point-based [4], curve-based [5], surface-based [6] and cage-based [7]. The cage-based paradigm is well-adapted to registration owing to its flexibility.

Concretely, we implemented our hybrid method with a Qt Graphical User Interface (GUI) shown in Figure 3. Our system is entirely controllable by tactile interaction and may be used in a fast and intuitive manner. We compared our method named *hybrid biomechanical* (HB) quantitatively in two ways against two previous methods [15], named *manual rigid* (MR) and [2], named *automatic biomechanical* (AB). The first evaluation uses a silicone liver phantom faithfully reproducing the shape of a patient’s liver obtained from CT reconstruction. The phantom was deformed and we used Structure-from-Motion to reconstruct its ground-truth 3D shape. The registration was then tested for 20 views from 4 different deformation datasets (5 views per dataset). The registration error, defined as the average distance between vertices of the preoperative and ground-truth models, is reported in Table 1(a). The registration error was evaluated for the visible and hidden parts. The second evaluation uses 8 images from 8 patients and had registration solved by our system under the control of 8 surgeons. The registration variability, defined as the root mean square of the standard deviation of the vertex positions, was evaluated for the visible and hidden parts.

2 Related Work

2.1 Liver Registration

We review related work on the biomechanical registration of a preoperative 3D model to laparoscopy. This is split in methods using the image contents only in monocular laparoscopy and methods using other modalities or sensors.

Monocular laparoscopy. Methods [1, 2, 8] process a single laparoscopy image with manually marked contour constraints representing the visual cues. More specifically, [1, 2] rely on contours, namely the falciform ligament and inferior ridge, and the silhouette, whereas [8] relies solely on the silhouette. Method [2] also uses a shading cue while [1] exploits environment priors modeling the effect of the pneumoperitoneum and gravity. Exploiting these environment priors remains difficult *in vivo* because of the unknown boundary conditions involving the viscera. These methods share the strong advantage to be compatible with regular laparoscopy but are limited by their weak registration accuracy.

Non-monocular laparoscopy. Method [9] uses a stereo-laparoscope to reconstruct the visible surface of the intraoperative liver shape. The liver’s 3D contour boundaries are then automatically detected on the visible surface and used to constrain registration. Method [10] also uses a stereo-laparoscope to reconstruct surface patches of the intraoperative liver shape. The stereo laparoscope is tracked using an optical tracking system. This allows one to local-

ize the patches in world coordinates and use them to constrain registration. Method [11] uses a tracked stylus to let the user enter landmarks on the liver surface. Because the pose of the landmarks is known, they directly serve as registration constraints. Method [16] uses intraoperative CT scans to constrain registration. Finally, method [12] registers an intraoperative CT scan to the laparoscope by imaging the laparoscope’s distal end itself within the CT volume and combining this with shading. These methods share a dependency on non standard laparoscopy or special hardware to solve registration. Nonetheless, with the exception of [16], they do not address the problem of registering the liver’s hidden parts.

2.2 Shape Editing

Shape editing refers to the change of a model’s surface through a set of handles either part or connected to it. Existing approaches can be divided in four main categories, depending on how such handles are distributed: point-based [4], curve-based [5], surface-based [6] and volume-based deformations [7]. In a point-based approach, the user provides a set of point displacements, each comprising a point along with its intended motion and region of influence. When these points are moved, the object is then warped to match the displacement constraints [4]. In curve-based approaches, the deformations are controlled by one or more curves. The deforming object is distorted to map from the source to the destination curves [5]. The surface-based approaches consist in deforming the object when a surface patch is modified by translating a set of control points. One of the main difficulties is to find a way to attach sample points on the object to the deforming patch [6]. The volume-based approaches use a cage that embeds the deforming object. This cage can have a fixed shape such as a cuboid [7], or can be even generated according to the shape of the object to be deformed [13]. The shape of this cage is altered by repositioning control points. The resulting cage distortion is then transferred to the embedded object.

3 Hybrid Registration

We first describe the principle and pipeline of our method. We then describe our implementation of the biomechanical model and the visual cues constraints. We finally show how these integrate with cage-based user interaction.

3.1 Principle and Pipeline

Our hybrid registration method takes as input a preoperative 3D model and a single laparoscopy image. Its principle is to combine a biomechanical model and the manual and automatic registration approaches. These respectively use user interaction and visual cues extracted from the image to solve for registration. Our method thus rests on three sets of constraints. The first two are borrowed from [2]. These are a biomechanical model based on the Neo-Hookean elastic model and the use of the falciform ligament and in-

ferior ridge as curve correspondences, and the silhouette. The third set of constraints are the cage-based constraints to model user interactions. Concretely, the preoperative 3D model is represented by a tetrahedral mesh and optimization follows the principle of position-based dynamics [14].

The pipeline of our method is illustrated in Figure 2. It has 7 main steps. The first two steps are similar to [2]: in step (1), we mark the falciform ligament, inferior ridge and silhouette on the laparoscopy image and in step (2), we mark the corresponding contours on the preoperative 3D model. In step (3), the system generates a cage enclosing the preoperative 3D model, to be used for user interaction at step (6). In step (4), the cage’s control points and the preoperative 3D model are co-triangulated in order to obtain a single tetrahedral model. In step (5), an initial registration is computed using only the visual cues, following an automatic method [2]. This initial registration is required to initiate interactive registration. In step (6), the user interactively edits the registration by moving the cage’s control points. The registration is updated in real-time to provide the user with live feedback. Importantly at this step, both the cage’s control points and the visual cues are used to update the registration. Finally, once the user is satisfied with the registration, step (7) augments the laparoscopy image with hidden anatomical elements brought from the preoperative 3D model.

3.2 Biomechanical Model and Visual Cues Constraints

The biomechanical model is created by augmenting the preoperative 3D model with the isotropic Neo-Hookean elastic model [14]. The associated mechanical parameters are set to generic values, namely the Young’s modulus to $E = 60,000Pa$ and Poisson’s ratio to $\nu = 0.49$. The contour constraints rely on anatomical landmarks which are the ridge, the falciform ligament, and the silhouette contours to constrain the deformation. The ridge contour is formed by the negative imprints of surrounding organs and has a very distinctive profile. The falciform ligament attaches the liver to the abdominal wall. It is located in the separation zone between the left and right lobes. It is cut in early stage during the surgery to make the liver move freely. Its insertion is then made clearly visible on the liver external surface. These two sets of contour fragments are stationary. Their correspondence with vertices in the preoperative 3D model remains the same during the entire registration procedure. The last set of contours is composed of the liver silhouette, imposing the liver model to not deform beyond those boundaries. Unlike for the ridge and the falciform ligament contours, the silhouette contours are not stationary and the associated set of constraints updated during the registration procedure. All these contour constraints are introduced in the optimization algorithm using an Iterative Closest Point (ICP) technique.

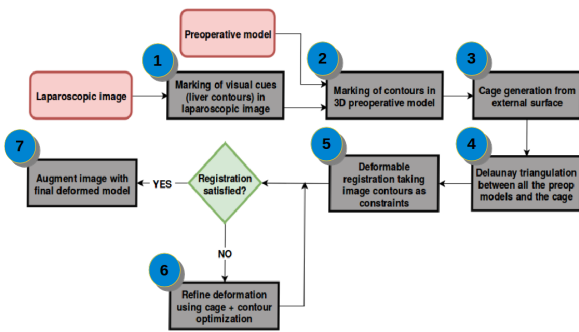
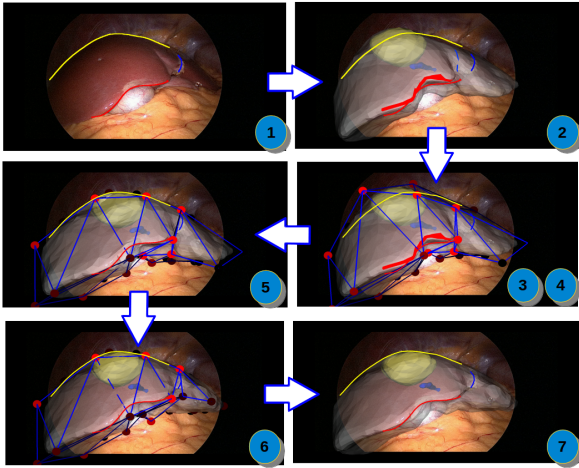


Figure 2 – Pipeline for the hybrid 3D to 2D deformable liver registration method. The contours associated to the silhouette, the falciform ligament and the ridge are marked in yellow, blue and red, respectively. The cage is rendered in blue wireframe and its associated control points with red dots.

3.3 Cage-based User Interaction

An intuitive and easy to use interface allowing one to edit the liver’s shape while respecting the biomechanical and visual constraints must be proposed. This is achieved through the use of a *nested cage*. This has a good trade-off between editing flexibility, namely the possibility to edit at an appropriate spatial frequency, and user friendliness. The nested cage is represented by a mesh composed of a very limited number of control points. These are obtained following the cage initialization procedure defined in [13] so that the cage encloses the input preoperative 3D model. An example of a generated cage is shown in Figure 1.

Making the constraints derived from the cage movable during the optimization procedure is not trivial. We propose to embed once and for all the cage’s control points into the volumetric model of tetrahedral topology built from the preoperative 3D liver model. Another possible solution would consist in creating a cage according to the model deformation at every iteration which would however significantly harm the software usability. When a cage’s con-

trol point is moved during the optimization, all the vertices belonging to the liver model adjacent to it are moved accordingly. This allows one to handle a set of vertices simultaneously over a model region. These deformations are compensated by the constraints described in the section 3.2 at the same time. During the optimization, a single iteration of the contour-based optimization is run for every change in position of the cage vertices in order to increase the responsiveness of the deformation.

4 Tactile Graphical User Interface

The proposed Graphical User Interface is shown in Figure 3. It is divided in four sections. First, the visualization area in which the laparoscopy image and the preoperative 3D model are shown. The user can position the preoperative 3D model and mark the contours using tactile gestures or the keyboard and mouse. Second, the left toolbar, which is used to either import or export the laparoscopy image and the preoperative 3D model. Third, the right toolbar, which is used to modify the appearance of the preoperative 3D model, to mark the visual cues and to launch registration. Fourth, the bottom toolbar, which controls the size of the visualization area, lets the user activate the cage-based editing mode, and implements miscellaneous other functionalities.

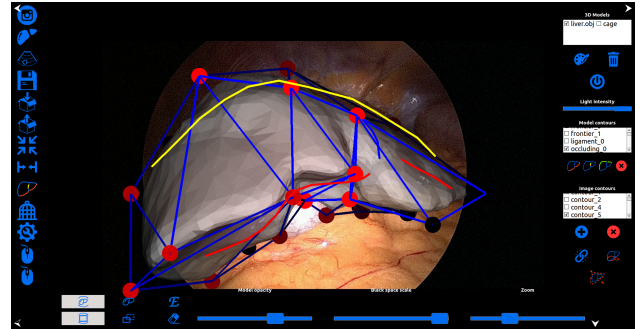


Figure 3 – Proposed tactile Graphical User Interface for our hybrid method.

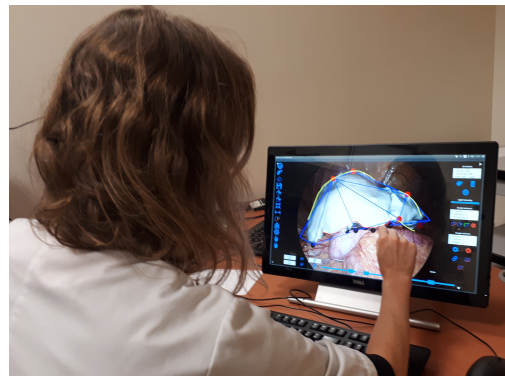









Figure 4 – A surgeon solving registration with the proposed Graphical User Interface.

Registration begins with a user click on  to set the laparoscope parameters obtained from a prior calibration procedure. The button  is then used to load the laparoscopy image and the button  to load the preoperative 3D model. The visual cues are marked both in the laparoscopy image and the preoperative 3D model with the help of the controls located in the right toolbar. A rigid registration is done automatically so that the preoperative model fits the liver approximately in the laparoscopy image. The nested cage is generated by clicking on . The user then proceeds to match the contours by clicking on . The preoperative 3D models can be then translated and rotated so that they approximately fit the image. Automatic contour-based deformation is then launched by clicking on . Once it completes, the user can proceed to edit the registration using the cage by clicking on the button . The vertices of the cage may be dragged while the system displays the registration combining the visual cues and the cage in real-time.

5 Experiments and Results

This section is divided in two parts. In the first part, results of an accuracy evaluation of the registration on a liver phantom are reported. In the second part, results of reliability evaluation on in-vivo liver data obtained at the hepatobiliary and pancreatic surgery department of the CHU Estaing hospital in Clermont-Ferrand, France, are reported.

We recall that in case of pathologies such as colorectal cancer liver metastases (CRLM) and hepatocellular carcinoma (HCC), a resection margin of 1 cm should be considered if possible [18, 19]. Thus, we consider a registration error of a centimeter or less as successful.

5.1 Accuracy Evaluation on a Liver Phantom

The accuracy of the proposed registration method is evaluated using a 3D printed liver phantom made of silicone (Figure 5(a)), which can simulate the bio-mechanical properties of a real liver. The principle of this experiment is as follows. The liver phantom is deformed and its shape reconstructed using the Structure-from-Motion software Agisoft Photoscan [17] (Figure 5(b)). N different views from those used to reconstruct the shape are taken as input images for the registration procedure. The CAD model from which the phantom has been printed is used as the input preoperative 3D model in our software and is registered following the proposed registration method. This experiment is performed for $M = 4$ phantom deformations and $N = 5$ different views per deformation.

We compared our method named *hybrid biomechanical* (HB) quantitatively in two ways against two previous methods [15], named *manual rigid* (MR) and [2], named *automatic biomechanical* (AB). The registration error, defined as the average distance between vertices of the preoperative and ground-truth models, is reported in Table 1. As we compared the distances between all the vertices and not only the ones used to perform registration, we can think

of it as a measurement of a target registration error (TRE) [20]. We report the errors for two classes of vertices: the entire registered model and its visible part.

Registration error for whole liver (mm)			
Dataset ↓	MR	AB	HB
1	09.00	05.35	04.10
2	06.19	08.65	05.05
3	12.23	10.32	08.46
4	08.60	06.78	05.70
Registration error for visible part (mm)			
Dataset ↓	MR	AB	HB
1	11.09	07.96	04.62
2	06.77	07.78	04.11
3	12.67	09.43	05.60
4	10.46	06.67	07.80

Table 1 – Registration errors with respect to the ground truths. The errors are expressed in millimetres and correspond to the average of the deviations of the registered model’s vertices.

5.2 Variability Evaluation on in vivo Liver Data

A high variability of the results obtained by different operators is a sign of unreliability of the registration solutions. We propose to assess the variability on real patient’s data. To this end, we collect eight different surgery datasets. We asked eight surgeons to perform the registration on each dataset which leads to a total number of 64 registrations. Before performing the cage-based registration, the surgeons are provided with short videos acquired during the surgery’s exploratory stage. The laparoscope was inserted in different trocars to let the surgeons have a wider scene perception. Table 2 reports the average of the vertex-to-vertex RMSD for datasets obtained from eight laparoscopic hepatectomy.

Patient →	1	2	3	4	5	6	7	8
Whole liver	07.05	11.19	12.23	20.33	08.12	08.63	12.34	08.01
Visible	06.95	11.09	08.12	15.66	05.52	04.50	06.26	04.19
Tumour	05.99	10.83	07.24	18.77	04.19	03.37	09.00	08.63

Table 2 – Registration variability (in mm) of three sets of model parts for the patient data.

6 Discussion and Conclusion

For the phantom data, HB shows the lowest registration error, well below 1 cm. The error of MR is noticeably high, usually greater than 1 cm, showing that the deformation is significant. The registration error of AB is overall lower than MR’s. The visual cues in AB thus sufficiently constrain the biomechanical model. HB shows decreased registration error thanks to the possibility of correcting the misaligned parts while respecting the anatomical and biomechanical constraints.

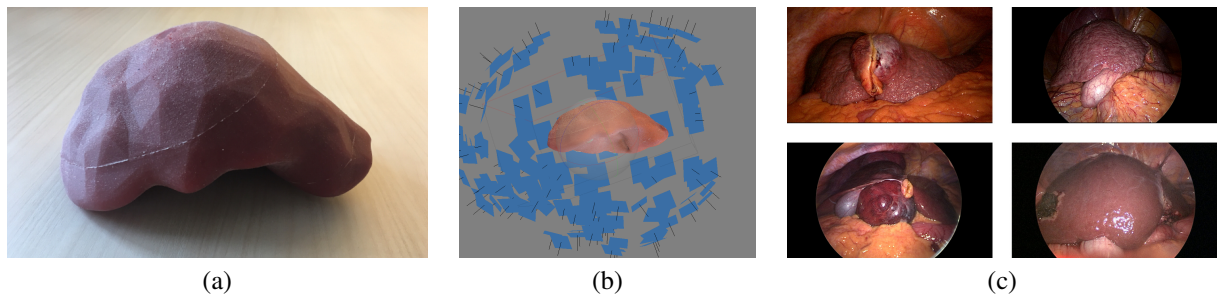


Figure 5 – (a) 3D printed liver phantom used for accuracy evaluation of the proposed registration method. Once deformed, its shape is reconstructed using Agisoft Photoscan. (b) Reconstructed cameras (in blue) and deformed phantom shape (in the center) in Photoscan. (c) Excerpt of real laparoscopy images used for variability evaluation.

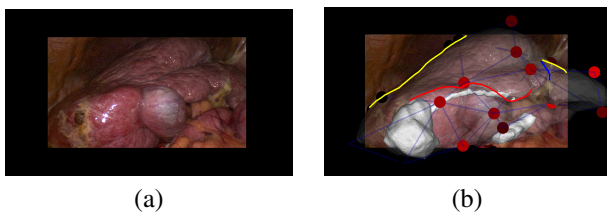


Figure 6 – Dataset associated to patient 4 presenting the highest registration variability (cf. Table 2). (a) Input laparoscopic image. (b) Result of the proposed registration. The registration procedure is very challenging especially due to the liver viewed from a very skew angle.

For the patient data, the variability across different users is of 7.79 mm on average which shows that HB passes the requirement of a low variability. The image of patient 4 was far more challenging than the others due to a lack of visibility of the liver, explaining its high variability (see Figure 6).

The phantom data show that the average registration error is of 5.83 mm for the whole liver and 5.53 mm for the visible parts with our hybrid method. This is very promising as being below the 1 cm oncologic margin advised in the literature for tumour resection in laparoscopic hepatectomy. However, further clinical tests have to be made in order to validate our method, notably regarding the location of inner structures such as tumours and vessels after registration. If such tests confirm an overall registration error lower than 1 cm, then the proposed method will give surgeons a reliable basis to guide resection. In future work, it will also be important to estimate the registration uncertainty and to relate it to the registration error to discard automatically ill-constrained cases such as the image of patient 4.

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