Deformation-based Augmented Reality for Hepatic Surgery

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Abstract. In this paper we introduce a method for augmenting the laparoscopic view during hepatic tumor resection. Using augmented reality techniques, vessels, tumors and cutting planes computed from pre-operative data can be overlaid onto the laparoscopic video. Compared to current techniques, which are limited to a rigid registration of the pre-operative liver anatomy with the intra-operative image, we propose a real-time, physics-based, non-rigid registration. The main strength of our approach is that the deformable model can also be used to regularize the data extracted from the computer vision algorithms. We show preliminary results on a video sequence which clearly hilights the interest of using physics-based model for elastic registration.

Keywords. Image-guided Surgery, Augmented Reality, Minimally Invasive Therapy, Soft Tissue Modeling, Real-time Simulation.

1. Introduction

Non invasive techniques commonly used for diagnosis and therapy include laparoscopic surgery and interventional radiology. While both approaches can be used for the treatment of hepatic tumors, laparoscopy is by far the most commonly used. However, hepatic resection and tumor removal using a laparoscopic approach remains a major challenge. Besides the requirement for advanced technical skills, the main issue is the transfer of the planned resection strategy (performed on the pre-operative data) into the operating field. While resection planes, vascular structures and tumors can be identified in the pre-operative CT or MR scan, and potentially reconstructed in 3D, they cannot be visualized during the procedure. To overcome this issue, a number of research groups are developing augmented reality techniques to overlay vessels, tumors and cutting planes onto the laparoscopic video. However, current techniques are limited to a rigid registration of the pre-operative liver anatomy onto the intra-operative image, and often this registration is not performed automatically. The objective of this work is to develop an automatic, real-time, non-rigid registration and tracking of the intra and pre-operative liver data.

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2. Augmented Reality in Laparoscopic Surgery

Augmented Reality (AR) is a general term describing the visual overlay of computer-generated images over real world images, in a spatially and temporally registered fashion. Typical applications of augmented reality are advertising, gaming, and support for complex environments such as military equipment, or maintenance in aviation. In medicine, augmented reality can have very different interpretations depending on the imaging modality.

In the last few years, non-rigid surfaces augmentation has been a topic of interest of many scientists. According to the context, non-rigid registration and augmentation can be realized directly from 2D images [2] or take advantage of a 3D model of the shape. When the texture information on the object is rich enough, many points can be matched between images, allowing a 2D deformation motion model to be computed. Bartoli *et al.* [1] used a direct method to register non-rigid pairs of images. It uses Radial Basis Mapping as an equivalent to optical flow constraint regularization approach [2]. In contrast to direct methods Pilet *et al.* [3] proposed a fast and robust tracking for large deformations. This approach used a wide baseline features matching and combine 2D deformable meshes with a robust estimation technique. Zhu *et al.* [4] proposed an approach to reduce the number of iteration of the previous method by using a progressive Finite Newton algorithm and an efficient factorization method to solve the optimization problem. In his approach Gay-Belille *et al.* [5] consider the occluded pixels as self-occlusion area that forces the wrap to shrink instead of outliers. Inspired by this self-occlusion shrinking, Hilsmann *et al.* [6] proposed an approach exploiting an optical flow constraint regularization by a 2D deformable mesh. The advantage of such methods is that they can be applied with monocular images but they require that rich information texture is available. Another restriction is that augmentation can only be realized onto the surface of the object. Thus AR medical applications where virtual objects may be added in depth can not be handled by such techniques. To cope with this problem, 3D deformable model have been considered. The deformation can be guided by monocular images [21] [20] or directly by 3D features available on the surface acquired with stereoscopic or depth camera as in [7]. One of the difficulty of these approaches is to define an appropriate deformation model. Most of the time, it is computed from a representative sample of possible shapes using a dimensionality reduction process.

In the area of Augmented Reality for surgical guidance, Suthau *et al.* [8] presented a concept work for AR in medical applications using a Head-Mounted Display. Since then, a number of medical AR systems have implemented the concept. In the MEDARPA (MEDical Augmented Reality for Patient) [9], an AR system for supporting MIS, only rigid transformations between the pre and intra-operative images were considered and computed from markers attached to the patient's body. Marescaux *et al.* [10] reported the first real-time AR-assisted laparoscopic adrenalectomy using manually assisted deformable registration. Yet many challenges remain to be solved in order to obtain real time fully automatic registration methods for deformable organs without the need to fix markers to the patient. A number of techniques have been proposed to increase accuracy of tracking and registration of AR systems in surgery. A hybrid tracking method for surgical augmented reality was proposed by Fischer *et al.* [11]. Still in the context of rigid registration, the system combines IGS equipment for infrared tracking and image-based tracking and is capable of superimposing tumor in video see-through AR and tracking instruments. Fuchs *et al.* [12] proposed an AR visualization for laparoscopic surgery. The benefit of their work was the extraction of depth from the laparocopic camera. Inside-out tracking was proposed by Teber *et al.* [13]. With their technique, navigation and superimposition of virtually created images and real-time images is possible with an error margin of only 0.5 mm. The process is simplified by the use of navigation aids placed close to the area of navigation targets. Su *et al.* [14] proposed a feature-based approach for AR for laparoscopic renal surgery with a 1 mm error in registration accuracy. To the best of our knowledge, the problem of considering deformable organs in AR systems is only addressed in a very restricted number of papers and only when 3D intraoperative imagery is available. In [19] a 4D model of a beating heart is built preoperatively from CT images using non registration techniques. The appropriate model is then used intraoperatively thanks to the information given by the ECG. Nicolau *et al.* [15] in a recent state of the art paper about the use of AR in surgical oncology conclude that if the feasibility of automatic AR systems on soft organs has been demontrated, they are not robust enough due to the high complexity of developing a real-time registration taking organ deformation and human movement into account.

In this paper, we propose a new real time, physic based system which demonstrates promising results for fully automatic registration of deformable organs when a stereo endoscope is used.

3. Methods and Materials

The overall computational flow of our method involves two main problems : 3D motion estimation of visual features and computation of the deformation. The key idea of our method is to use a physics-based model guided by 3D points of the liver computed from the intraoperative stereovision data. The use of the mechanical representation is twofold: first, it allows to recover a physically coherent elastic deformations of the object and second, we use this model to filter out possible erroneous 3D points built from stereovision. This is done through the use of a set of control points whose motions are guided by the 3D features. These steps are illustrated in Figure 1.

To estimate the motion of the surface of the liver, salient landmarks have to be detected and tracked over time. Many methods have been investigated for tracking organs surfaces in laparoscopic images [16] [17]. Our tracking system is based on Elhawary *et al.* [18] method. This method uses the the Speeded-up robust features detector (SURF) [22] and the Lucas-Kanade (LK) optical flow optical flow for the tracking stage. This combination has proven to be robust to track heart motion in laparoscopic images. In our system the tracking stage based on the optical flow is coupled with a Kalman filter that smoothes the features displacement, thus eliminating possible false displacements.

In order to constrain the mechanical model to fit the liver motion we define a set of control points. Features extracted from laparoscopic images may be poorly distributed over the target surface and therefore feature-dense area may be over-constrained whereas feature-sparse area may not be constrained. This set of control points, is generated using ray-casting on the surface with different patterns. The density of the control points set is selected using an a-priori of the stiffness of the target (soft targets require a dense set of control points to be able to capture all the possible deformations).

The control points and the features built from stereovision are linked through clustering (cf Figure 2). Each control point is linked with its nearest neighbors in a radius

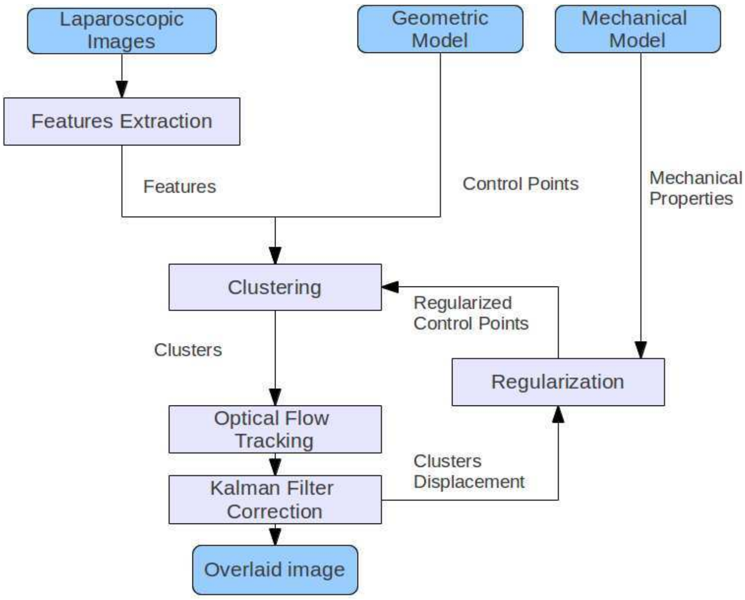

Figure 1. Computational flow of our method: The main contribution relies on the combination of the tracking and the mechanical representation.

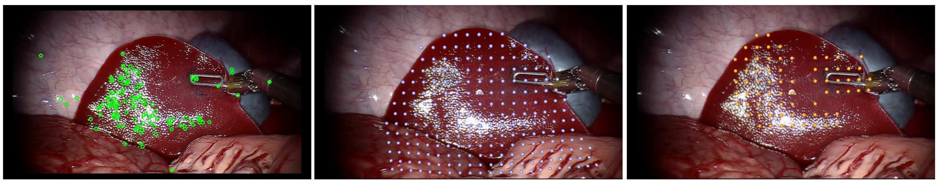

Figure 2. Clustering phase : (Left) A set of detected features using SURF detector. (Middle) The projected control point on the surface of one lobe of the 3D model of the liver. (Right) The selected control point linked to the detected features.

defined by bio-mechanical model. A weight is assigned to each neighbor calculated by a weighted mean based on the combination of the SURF Hessian response and an Inverse Distance Weighting on the neighbors distance.

Finally, The control points set whose motion is guided by the features are used as external constraints of an underlying mechanical representation of the target. The use of the mechanical representation is twofold: first, it allows an estimation of the whole volume given partial surface deformation and second it serves as a regularization step where it can limit the influence of the features with bad depth estimation. In our case, tetraheadra-based FEM model is used whole mechanical parameters (Young modulus, Poisson ratio) are taken from the literature. The Figure 3 illustrated the mechanical FEM model.

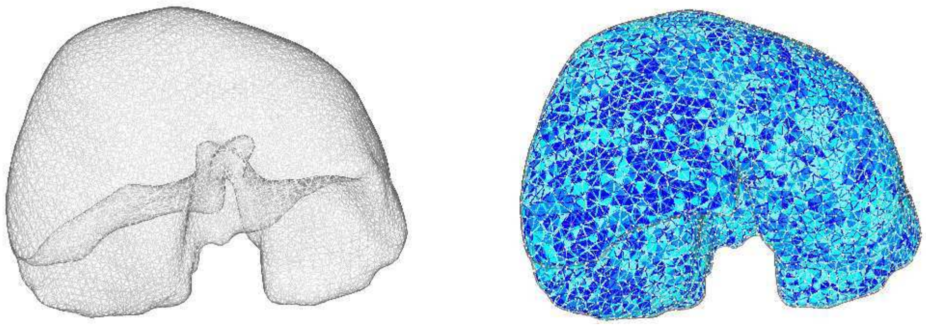

Figure 3. 3D model of the Porcine Liver reconstructed from pre-operative CT Scan : (Left) Mesh in wire-frame. (Right) Volumetric mesh composed of tetrahedra.

4. Results

We have tested our approach on a video of a porcine liver surgery acquired from a Da Vinci System with a resolution of 800×450 and a frame-rate of 30 fps. The tracking system shows it robustness in presence of specularity and large liver deformations. Only a few features are lost during the deformation (less than 7%).

The whole framework allows to interactively capture and track the surface deformations of the porcine liver in real time and at the native video frame-rate (25 fps up to 30 fps). With the underlying mechanical representation as a regularization step, we are able to get the deformation of the visible lobe of the liver and are able to represent vessels that can be superimposed on the laparoscopic video images.

The Figure 4 illustrates the results of our method at selected frames.

5. Conclusions and Discussion

When dealing with complex minimally invasive procedures such as tumor resection, the ability to overlay important anatomical information could offer many benefits. In this paper we present a new physics-based approach for the tracking and registration of pre-operative data (planning strategy and anatomical structures) onto the real laparoscopic video images. Preliminary results exhibit that our approach can track and handle target deformation allowing interactive overlay of internal data such as vascular network (or tumors) in order to help the surgeons during the procedure.

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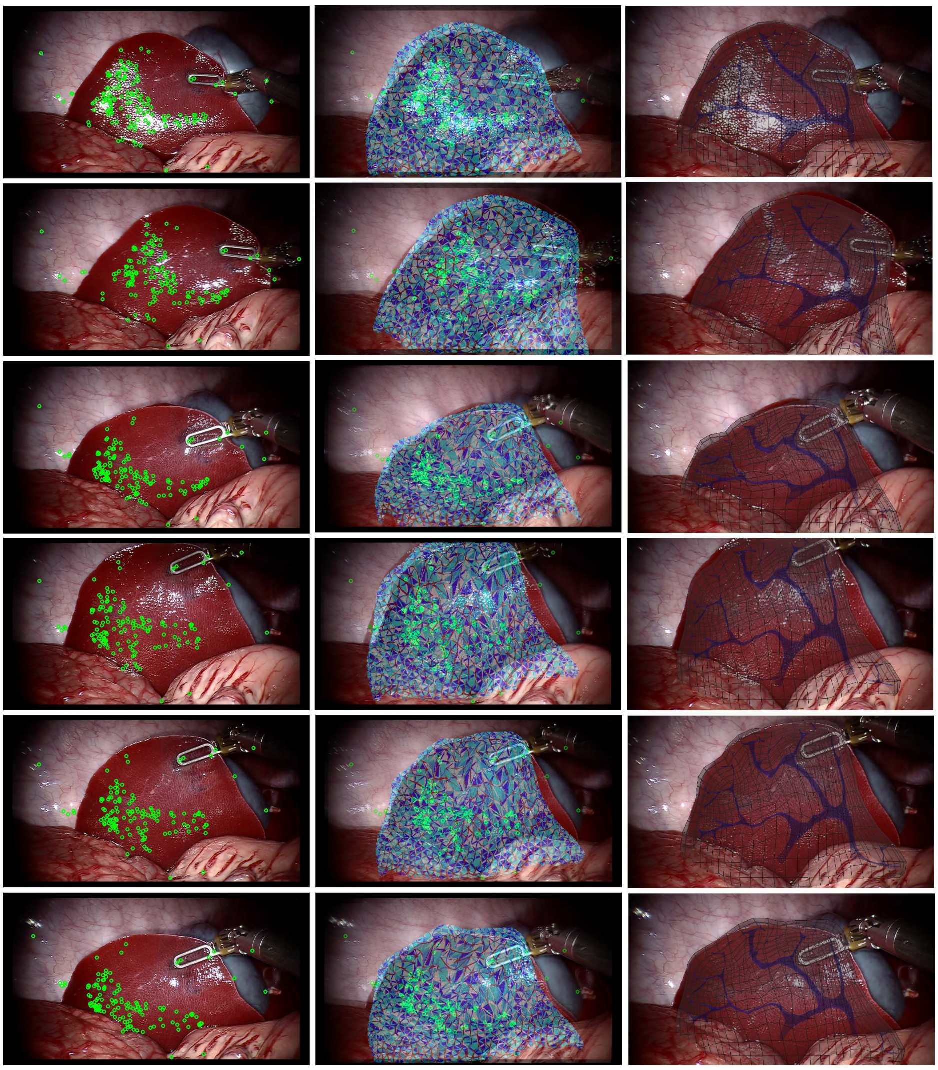

Figure 4. Sequences of images showing our method at selected frames : (Left) The features being tracked in presence of specularity and large deformation. (Middle) Biomechanical finite element model of the liver lobe being deformed using the control points. (Right) Overlaid mesh of the virtual liver in wireframe and vascular network in blue.

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