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Augmented Reality for Video-Based Endoscopic Surgry

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Abstract: In this study a one step method is proposed for 2D/3D registration and automatic reconstruction of deformable digestive human organs when making a laparoscopic cholecystectomy in order to build an automatic marker less intraoperative surgical augmented reality system using different image sources such as 2D coloured laparoscopic images or patient specific CT-Scan or MRI data and anatomical knowledge. The method is based on a novel multi-resolution analysis of 2D and 3D scenes using wavelets guided by anatomical trees for reconstruction and surface segmentation of abdominal organs. We take in consideration several laparoscopic standard surgical procedures for enhancing and auto-building of the correspondent deformable 3D model.

Key words: Wavelet deformable reconstruction laparoscopic augmented reality

INTRODUCTION

Augmented reality is a new research area located at the intersection of various important domains especially 3D image synthesis and computer vision. Unlike virtual reality, which emerge totally the user in an environment composed only of 3D virtual objects, augmented reality deals with the problem of inserting virtual 3D objects in a scene taken from the real world. In augmented reality applications, we have to find the correspondence between 3D model and 2D images, detect occlusion, calibrate the camera and extract geometric and illumination features of the real scene so that virtual objects appear as real as possible. One can find different commercial, military and educative applications of augmented reality[1,2].

In the medical and surgical area, virtual and augmented reality can provide a major improvement by guiding the intra-operative surgical gesture, training and planning on naive virtual model or constructed using specific patient data taken preoperatively, such as CT-Scan or MRI images. Furthermore, augmented reality allows superimposing of the preoperative 3D modelling of the patient on its intra-operative real view.

Virtual reality surgical systems led to simulation surgical intervention using a virtual model, without exploiting really the patient data. Computer assisted surgery systems use the 3D model of the patient constructed using preoperative medical images to plan and train the surgical gesture before carrying it out. 3D virtual models can be used to diagnostic pathologies or to determine the critical zones to avoid during the intervention. Therefore, the practitioner is limited to a virtual copy which can considerably differ from the real situation of the patient during the real intervention.

In order to overcome this limit, augmented reality surgical systems offer the opportunity to the registration of the preoperative virtual model and real information taken in-vivo in the operating room of the patient to have a single spatial space linking the virtual and real worlds.

Today, Several computer assisted surgical systems are used to enhance and assist the surgeon action. The growing demand of complex, precise and mini-invasive surgery is driving the development of more enhanced and innovative systems. From engineering systems perspective there is two kind of computer integrated surgical systems (CIS), surgical CAD/CAM systems and surgical assistant systems[3]. Surgical CAD/CAM systems transform the preoperative patient specific data mainly medical images to a virtual model, help surgeon to establish an optimised surgical plan and detect pathologies. Surgical assistant systems work interactively with the surgeon in the operating room to give intra-operative decision support. However, the majority of certified systems deal with interventions on rigid parts of the human body such as orthopaedic or neural surgery.

Digestive organs are soft and complex to represent using the majority of existent 3D modelling techniques. Therefore, there are few clinical certified works about application of virtual or augmented reality in digestive surgery[4,5].

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Laparoscopic cholecystectomy is a mini-invasive surgery technique to remove the gallbladder throw a tiny incision of the navel. It is relatively a new method, compared to the open abdominal surgery techniques, but it is now a gold standard and applied for about 90 to 95% of cases. More information about this surgical method can be found in[6].

The computer assisted surgery over interactive medical intraoperative augmented reality systems can lead to major improvements in order to enhance the physician action especially in the case of laparoscopic cholecystectomy. The 3D modelling of the patient organs or surgical instruments is not only important to make simulation and planning of the surgical gesture as first preoperative step, but also to ensure an accurate superimposition of the virtual patient on the real-time acquisition realized during the intervention. Therefore, the proposed virtual model has to allow interaction on anatomical and pathological modelled structures, so as to reproduce the real surgical gesture performed by surgeons in the operative room.

Deformable organ modelling: The 3D modelling of patients from their CT-Scan or MRI is an important step, either preoperatively for improving planning and simulation, or during the intervention throw medical augmented reality systems. A survey for modelling techniques of free-form objects can be found in[7]. There are also some methods based on particle systems or sphere-filled objects for modelling deformable organs[8-10].

In this section, MRI medical image processing technique and a new automatic iterative 3D reconstruction method for the generation of a sphere-based virtual human digestive organ model are proposed.

The proposed method use the MRI medical images in order to build a spheres-based 3D virtual model of digestive human organs. This model is composed of only spheres with different volumes and an associated tree to determine the different associations and relations. Therefore, the model of the virtual organ can be considered as a volumetric model. Figure 1 shows the main steps of the proposed method.

The reconstruction method consists of the following steps described bellow;

Sphereleting MRI slices: This step consists of developing a 3D model composed of a set spheres for each MRI slice. The medical image is segmented using a threshold with the greatest interesting value T_0. Then, starting at the high-left pixel of the image, each row is scanned until a white pixel is found $P_{i,,j}$. A white pixel in MRI medical image of human digestive organ is assumed to represent an element of that organ which is clearly separable of other organs in thresholds interval [T_{min} T_{max}]. In order to build the modelling sphere, the bottom pixel $P_{i+1,,j}$ is scanned and processed. In the case where the bottom and right neighbouring $P_{i+2,,j}$ and $P_{i+1,,j+1}$ pixels are white, a bounding elementary sphere that we call a sphereletron is created around them. The same process is repeated recursively with the last bottom pixel and with each extension of the bounding sphereletron we double its ray. When no more white pixels can be found, the ray $R_{i\ j}$ of the current bounding sphereletron is saved in an associated matrix that has the same size as the processed MRI image, so that we put its value in the sphereletron centre position $P_{x,y}$. This matrix is called the sphereletron buffer (B). Thus, we have:

$$B_{x,y} = R_{i,j} \quad (1)$$

The Fig. 2 shows the process of sphereletron construction with a given a rotation and a scan direction. The pixels included in the created sphereletron are set to black and the process described above is repeated on the new image until it will be impossible to add new sphereletrons to the sphereletron buffer (B).

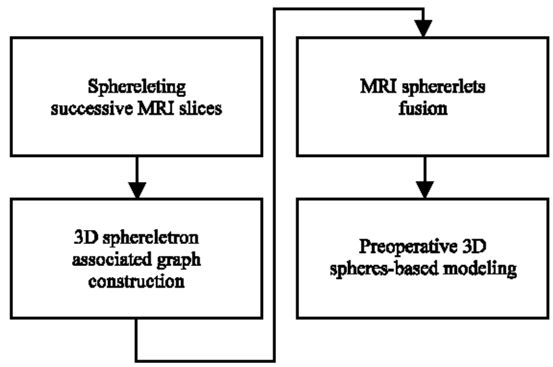

Fig. 1: Outline of the proposed automatic 3D reconstruction method

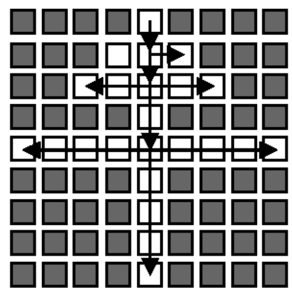

Fig. 2: Elementary bounding sphere construction

For this sphereleting step to be independent of the used threshold, it is important to repeat the process with more tolerant threshold that is smaller than the initial threshold T_0. Thus, we repeat the same sphereletron buffer (B) building actions until the number of sphereletrons will decrease. We propose to use a dyadic subdivision for determining new threshold T_t and thus we have for a given iteration t the value of the threshold :

$$T_t = 2^{(-t)}\, T_0 \quad (t = 1,2,...,max\text{-}min) \qquad (2)$$

Where max and min denote the indices limits of the aimed organ thresholds interval in its MRI image.

At the end of this step, a spheres-based model for each MRI slice is constructed and represents an approximation of the exact 3D model of the organ without taking in consideration anatomical information such as topological constraints.

Topological spheres associated graph construction: In order to build a 3D model taking in consideration the anatomical knowledge, an valued oriented graph (G) is constructed. First, for each MRI slice sphereletron model we build a 2D graph. Thus, if we denote the entire MRI slices in the form of the given images sequence of length n as $M = [m_1, m_2,\ldots, m_k, m_{k+1},\ldots, m_n]$ and the set of sphereletrons constructed for each MRI image and sorted according to ray value as the sequence $S^k = [S_1, S_2,\ldots,S_i,\ldots, S_{lk}]$ where l_k is the number of spheres of the m_k image, we have the arc S_{ij}^k that links the S_i and S_j spheres centres of the m_k image, then:

$$S_{ij}^k = C_i^k - C_j^k \quad (i < j, R_j^k = \max\{R_t^k, t = j+1\ldots l_k\}) \qquad (3)$$

Where C_i^k and C_j^k denote the centres of the spheres S_i^k and S_j^k respectively and R_j^k is S_j^k ray value. The value of the arc S_{ij}^k, noted $V(S_{ij}^k)$, is equal to 1 if there is an intersection between the two linked sphereletrons and zero if they are separable.

If we denote the subsequence of the length $(2R^k+1)$ in M as $M_k' = [m_{k-R^k},\ldots, m_{k+R^k}]$, with:

$$R^k = \min(k-1, n-k, \max\{R_i^k, i = 1\ldots l_k\}) \qquad (4)$$

The same process is repeated on spheres of M_k and other sphereletrons model associated to MRI slices. Figure 3 shows example of the topological graph construction.

Preoperative spheres-based models: The fusion of the n sphereletrons models developed allows to have a unique preoperative model. In order to make 2D/3D registration possible, the process of reconstruction is repeated on MRI slices with rotation in all the directions. Therefore, we have 360 preoperative sphereletron models to ensure the most possible accurate registration intraoperatively.

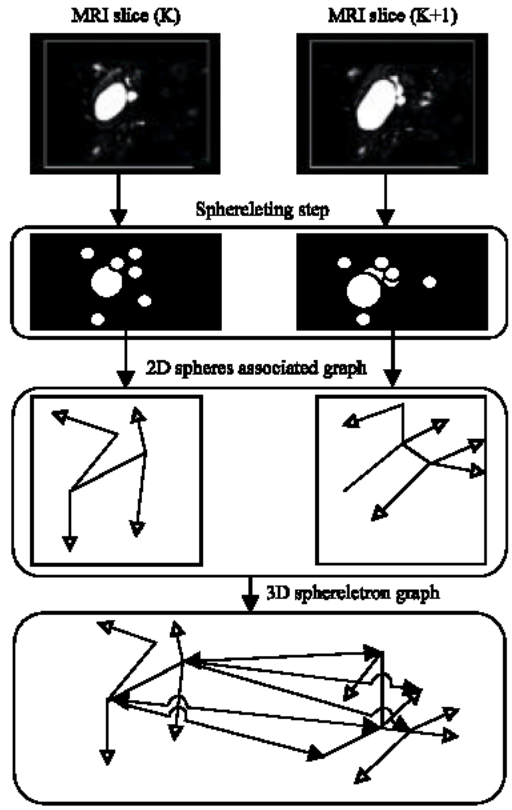

Fig. 3: Automatic 3D organ reconstruction

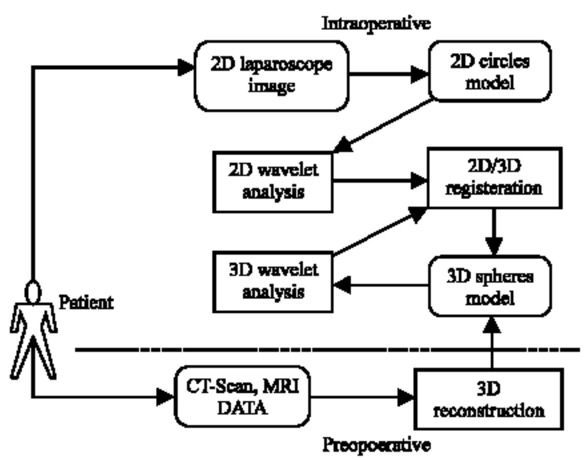

Fig. 4: The wavelet-based 2D/3D registration/ Deformation method

2D/3D non-rigid registration of deformable disgestive organs: In our method, we use the preoperative 3D modelling to 2D/3D registration with intraoperative laparoscopic video images and also to enhance and deform the preoperative virtual organ according to the surgical gesture. Figure 4 shows the detail flow of the proposed method.

2D sphere-based analysis of 2D images: A circular window is used to scan the image and according to the colour of its centre. We assume that the whole circle scanning window has the same colour as its centre, if (~100% - e) of the inner pixels have the same colour.

Wavelet transform of the spheres-based model: A new discrete wavelet transform method of 3D spheres-based models is proposed. We can formulate the transform, so as If I_r denotes the identity matrix and Θ_r the null matrix with order r, then S_j, the original set of spheres and D_j the detail part, j = 1,…,n, are computed as follows in the analysis phase:

$$S_j = (I_{2^{n-j}}, \Theta_{2^{n-j}})\, S_{j-1} \quad (5)$$

$$D_j = (-I_{2^{n-j}}, I_{2^{n-j}})\, S_{j-1} \quad (6)$$

while S_{j-1} (the coarsest level), j = n,n-1,…,1, is computed as follows in synthesis phase:

$$S_{j-1} = \begin{bmatrix} I_{2^{n-j}} & \Theta_{2^{n-j}} \\ I_{2^{n-j}} & I_{2^{n-j}} \end{bmatrix} \begin{bmatrix} S_j \\ D_j \end{bmatrix} \quad (7)$$

2D/3D registration using wavelet transform: The proposed wavelet is used to transform the circular scanning windows in the RGB space and the sphereletrons of the deformable model. The registration is based on comparing the wavelet coefficients in the D_j vector.

EXPERIMENTS AND RESULTS

The data source used is MRI video capture dataset from IRCAD[11]. We use 15 slices with dataset resolution of 240×320×15. We suppose that the MRI slices of the organ are parallel and the distance separating them is constant.

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