Coronary Motion Modelling for Augmented Reality Guidance of Endoscopic Coronary Artery Bypass

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Abstract. The overall aim of our project is to guide totally endoscopic coronary artery bypass. This requires construction of a 4D preoperative model of the coronary arteries and myocardium. The model must be aligned with the endoscopic view of the patient's beating heart and presented to the surgeon using augmented reality. We propose that the model can be constructed from coronary CT. Segmentation can be performed for one phase of the cardiac cycle only and propagated to the others using non-rigid registration. We have compared the location of the coronaries produced by this method to hand segmentation.

Registration of the model to the endoscopic view of the patient is achieved in two phases. Temporal registration is performed by identification of corresponding motion between model and video. Then we calculate photo-consistency between the two da Vinci endoscope views and average over the frames of the motion model. This has been shown to improve the shape of the cost function. Phantom results are presented.

The model can then be transformed to the calibrated endoscope view and overlaid using two video mixers.

1 Introduction

1.1 Augmented Reality Applications in Surgery

With the introduction of the da Vinci robot, totally endoscopic coronary artery bypass grafting (TECAB) can be performed on the beating heart. This provides less invasive surgery without the need for sternotomy or heart-lung bypass. However, the level of conversion to more invasive endoscopic procedures is reported to be 20-30% with the most likely causes being misidentification of the target coronary artery or difficulty in locating the vessel [1,2].

To investigate whether augmented reality (AR) guidance can improve TECAB, we have identified two critical points in the procedure. During harvesting of the

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left internal mammary artery highlighting the position of the bifurcation would allow surgery to progress rapidly to this point. After opening of the pericardium overlay of the target vessel would allow accurate location and identification. Accurate coronary vessel overlay requires alignment of a 4D preoperative model of the beating heart to the da Vinci endoscope view and AR visualisation.

2 Methods

To achieve guidance we require a 4D model of the beating heart. This must be both temporally and spatially registered to the patient. Finally the model must be visualised using the calibrated endoscope view.

2.1 4D Model Construction

The model of the patient's beating heart comes from coronary CT, which can be reconstructed at up to 20 multiple even phases throughout the cardiac cycle. The relevant vessels must be segmented along with the surface of the myocardium.

The motion of the heart can potentially be obtained from non-rigid image registration [3]. This means that the heart and coronaries need only be extracted in one frame and the shape in subsequent frames can be propagated by registration [4]. This has been demonstrated to give good results for the surface of the heart in animal studies [3]. However, we have found that the position of the coronaries is not always well predicted by registration. This could be due to the fact that though the surface is well aligned, cardiac twisting motion or sliding along the surface may not be detected by registration (see Figure 1).

A subdivision surface representation of the heart with volume preservation has been investigated to track the motion of the myocardium [5]. We have considered whether vessel enhancement, automated presegmentation of the CT data-set or the use of a 4D statistical model could be used to improve segmentation [6]. An example of a patient model can be seen in figure 4(a).

2.2 Registration Techniques

Having obtained a preoperative model of the patient we now need to align this model to the video view through the da Vinci endoscope.

Our strategy in performing registration will be to separate the temporal and spatial alignment of the preoperative model. Temporal alignment may be obtained using the ECG signal. However, there may be residual lag between the ECG and the video and we are investigating whether feature tracking in the video images could be used for this purpose.

Corresponding features in the left and right views in the da Vinci stereo-endoscope can provide 3D tracked points on the viewed surface. We propose this technique to measure the motion of the heart and to separate cardiac and respiratory motion. We are also examining whether geometry constraints can be used as an accurate means of finding the period of the heart cycle, in the presence of rigid motion of the camera or near rigid motion due to breathing.

Having established temporal registration, the remaining motion should be rigid. Preliminary work has shown that 3D-3D non-rigid registration can be used to build separate models of respiratory motion of the liver [7] and heart [8]. Since both respiratory and cardiac motion are smooth and continuous, we will develop 4D parametric motion models based on 4D B-splines.

To establish correspondence we are investigating two approaches. We are adopting a similar approach to that of [9] to reconstruct the motion of the viewed surface, which can then be registered to the preoperative 4D model. Secondly we are investigating whether intensity-based similarity metrics like photo-consistency [10] can be used.

2.3 Visualisation

In order to provide an AR facility for the stereo endoscope of the da Vinci system we need to establish the relationship between camera coordinates and image coordinates (determined by the intrinsic transformation parameters) as well as the relationship between world coordinates and camera coordinates (determined by the extrinsic transformation parameters). For camera calibration we use an offline camera calibration technique to determine these parameters [11].

As the image fusion is done by use of chroma keying with two video mixers, an additional 2D-2D transformation from the graphical output to the input channels of the mixer is needed. This is achieved by point to point registration.

We will then use the model-based 2D-3D registration algorithm described previously to estimate the extrinsic transformation parameters.

3 Results

3.1 4D Model Construction

For preoperative model building we use coronary CT images reconstructed at 20 even phases throughout the cardiac cycle. We segment the first phase by hand and propagate this to the other 19 phases by non-rigid registration [4]. This is similar to [3], but here it is demonstrated on clinical CT scans rather than animal data. Figure 1 gives an idea of the quality of the registration.

3.2 Registration to the Endoscopic View

Figure 2 shows the behaviour of the photo-consistency measure near the minimum for video images from a bench camera setup. As the number of phases of the phantom CT surface model used increases, the curve becomes smoother. This suggests that our strategy of performing rigid spatial registration but averaging temporally corresponding frames is sound. The resulting alignment using photo-consistency can be seen in figure 3. An initial registration is performed using manual point identification on the surface model and in both video images. The model is aligned iteratively so as to minimise the 2D projection error of the landmarks, which was found to be more robust than reconstructing 3D points

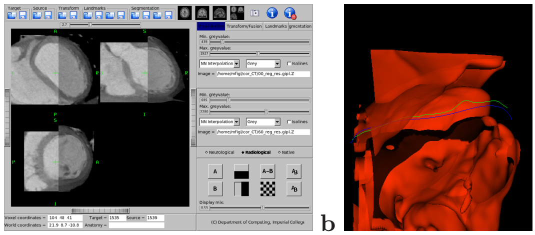
a b

Fig. 1. Non-rigid registration was used to register the first image to the other images. **a** shows the registered image slices from phases 0% and 60 % of the cardiac cycle; **b** shows an automated segmentation of the myocardium with aligned manual and registration-based vessel segmentations. Some discrepancy between the true vessel position and that from registration is seen.

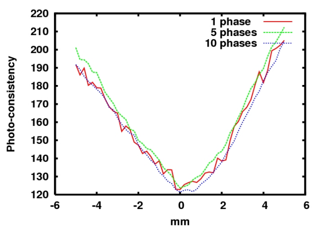

Fig. 2. Graph showing photo-consistency vs displacement near the minimum using 1, 5 and 10 phases of the phantom surface model. Noise and local minima are averaged out as more phases are used.

from the two video images and performing a 3D registration. There are still some inaccuracies as can be seen in figure 3(a). After photo-consistency registration the alignment is seen to be much better (figure 3(b)).

3.3 Visualisation

An example of retrospectively aligned images is shown in figure 4. We have a number of clinical coronary CT images that are being used to investigate preoperative model construction. Registration algorithms using both feature tracking and intensity-based techniques are being developed.

4 Discussion

We propose a system for augmented reality image guidance of totally endoscopic coronary artery bypass. Previous work has suggested the use of image guidance in TECAB surgery and demonstrated its feasibility on a heart phantom [12]. Falk et al have demonstrated a system for AR guidance based on multi-planar x-ray angiography [13]. We describe the first such results using clinical coronary CT scans to provide the 4D patient model using non-rigid registration. We

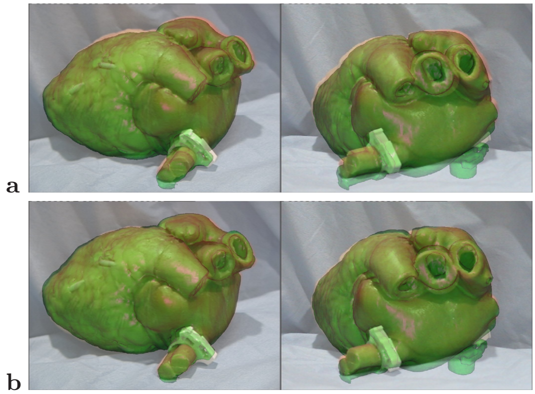

Fig. 3. Photo-consistency registration result from a bench camera setup, showing **a** the initial position from manual point-based registration and **b** the result of photo-consistency alignment. A clear improvement is achieved using photo-consistency.

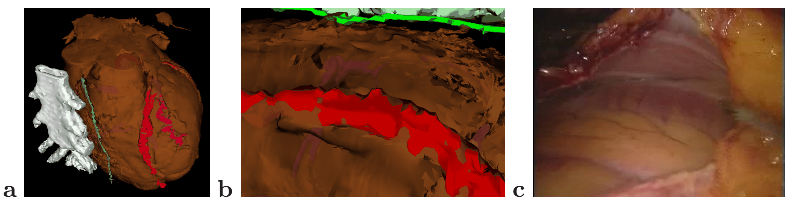

Fig. 4. A rendering of the preoperative model showing the myocardial surface, left internal mammary artery, left anterior descending artery and a diagonal branch (a), an aligned rendering (b) and its corresponding endoscope view (c)

also propose two novel strategies for alignment of this model to the endoscopic view. The first uses robust feature tracking to reconstruct the viewed surface, which can then be matched to the preoperative model. The second strategy uses intensity-based methods for registration. The latter has been demonstrated on a phantom images.

For augmentation of the endoscopic view we use chroma-keying by video mixers , which does not introduce any lag to the surgeons view of the real surface. It is hoped that such information can improve the efficiency of TECAB surgery and reduce the conversion rate to more invasive procedures.

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