Image Guidance for Robotic Minimally Invasive Coronary Artery Bypass

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Abstract. A novel system for image guidance in totally endoscopic coronary artery bypass (TECAB) is presented. Key requirement is the availability of 2D-3D registration techniques that can deal with non-rigid motion and deformation. Image guidance for TECAB is mainly required before the mechanical stabilization of the heart, thus the most dominant source of non-rigid deformation is the motion of the beating heart.

To augment the images in the endoscope of the da Vinci robot, we have to find the transformation from the coordinate system of the preoperative imaging modality to the system of the endoscopic cameras.

In a first step we build a 4D motion model of the beating heart. Intraoperatively we can use the ECG or video processing to determine the phase of the cardiac cycle. We can then take the heart surface from the motion model and register it to the stereo-endoscopic images of the da Vinci robot using 2D-3D registration methods. We are investigating robust feature tracking and intensity-based methods for this purpose.

Images of the vessels available in the preoperative coordinate system can then be transformed to the camera system and projected into the calibrated endoscope view using two video mixers with chroma keying. It is hoped that the augmented view can improve the efficiency of TECAB surgery and reduce the conversion rate to more conventional procedures.

1 Introduction

1.1 Augmented Reality Applications in Surgery

Augmented reality (AR) systems applied to surgery aim to overlay additional information, most often in form of images or renderings, onto the real view of the surgeon. Using a stereoscopic device has the potential advantage of enabling 3-D perception of both the surgical field and overlays, potentially allowing virtual structures appear beneath the real surface as though the tissue were transparent.

In this paper we describe a system for image-guided robotic surgical treatment of coronary artery disease. We aim to enhance the endoscopic view provided by

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the da Vinci robot with information from preoperative imaging. This requires construction of a fully 4D model of the patient from coronary CT, both temporal and spatial registration of this model to physical space and visualisation as overlays on the endoscopic view.

1.2 Clinical Need

Totally endoscopic coronary artery bypass (TECAB) has the potential to treat coronary artery disease without the need for invasive sternotomy or heart-lung bypass. However there is still a conversion rate to more invasive methods of 20-30% [1,2,3]. This can occur if there is misidentification of the target vessel or difficulty in locating the artery if it is hidden by fat.

We have identified two critical points in the procedure that might gain from intraoperative guidance. During harvesting of the left internal mammary artery the position of the bifurcation would be useful to know to allow surgery to progress rapidly to this point. After opening of the pericardium overlay of the target vessel will allow accurate location and identification. It is hoped that such guidance will make surgery more efficient and reduce the conversion rate for TECAB.

2 Methods

The layout of the system can be seen in figure 1.

The workstation has two dual output graphics adapters (nVidia Quadro FX 1500) that provide the overlays to each eye and a multiple input frame grabbing device (Active Silicon, Uxbridge, UK) for the purposes of registration.

Overlay on the view through the da Vinci is provided using two video mixers (Panasonic WJ-MX 50) with chroma-keying functionality. This ensures that there is no increased lag introduced by the system. An idea of the quality of chroma keyed overlay can be found in figure 2

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 preoperative model of the patient comes from coronary CT, which provides a fully 4D representation of the patient. The CT can be reconstructed at up to 20 multiple even phases throughout the cardiac cycle, see figure 3 for an example. The relevant vessels must be segmented along with the surface of the myocardium.

The motion of the heart can potentially be obtained from image registration [4,5]. We are investigating the use of a 4D statistical model to produce a segmentation [6] and also the use of a subdivision surface representation of the

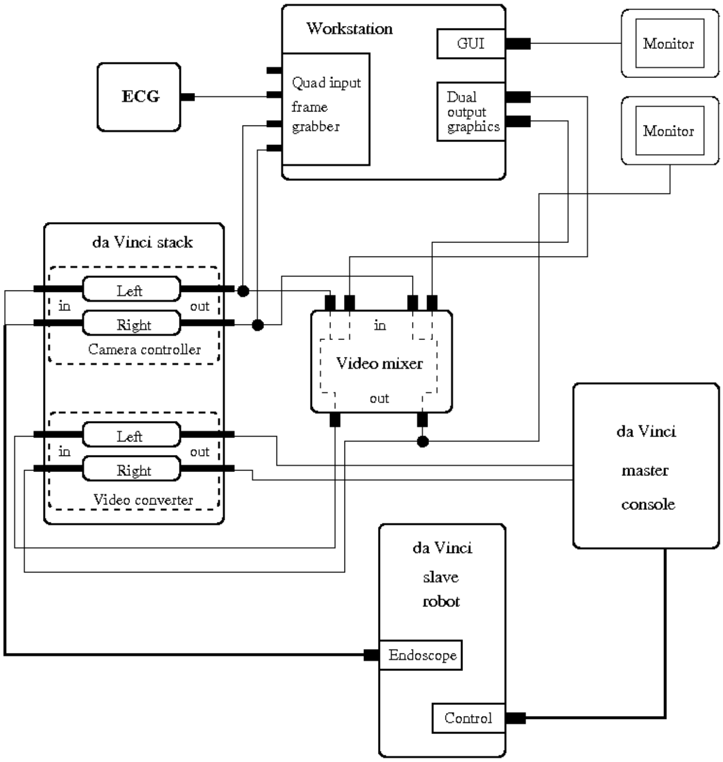

Fig. 1. The layout of the system in theatre. ECG and the stereo video are grabbed by the machine to gain parameters we need for the image overlay, as e.g. the heart and breathing frequencies. The resulting images from the dual graphics output are overlaid to the real video images using video mixers. There is no delay of the real video images in the view of the surgeon as they are just copied to our PC (there direct connection from the camera controller via the video mixer to the converter and the master console).

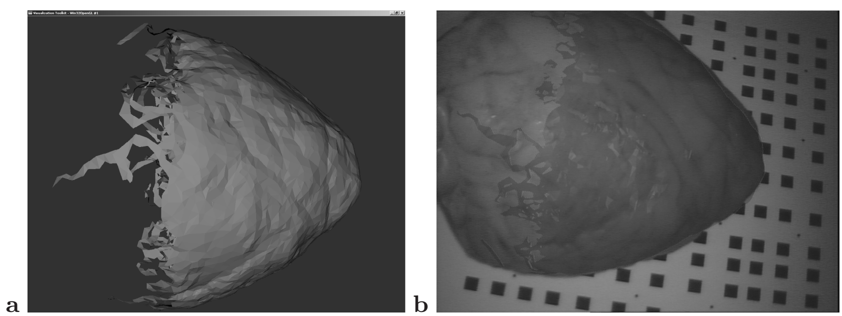

Fig. 2. The surface of a heart phantom and the overlay using chroma keying. **a** shows the rendering of the surface. The surface file is truncated to visualise the difference to the heart phantom underneath as can be seen in **b**.

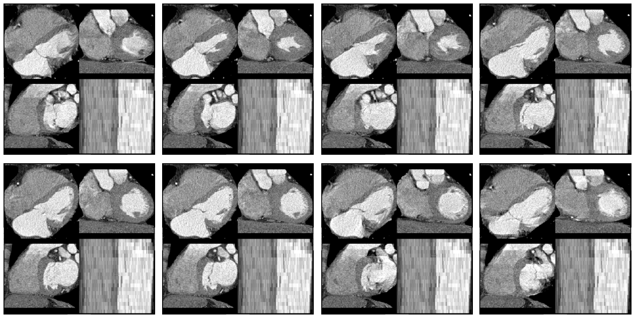

Fig. 3. The phases of a heart displayed using the software `rview`. Only about half of the 20 phases are shown.

heart with volume preservation to track the motion of the myocardium [7]. We will also apply the registration method in [8] to our volumes.

An example of a patient model can be seen in figure 6(a).

2.2 Model-Based 2D-3D 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. In this step we will develop suitable non-rigid 2D-3D registration algorithms.

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, e.g. in figure 1 the video output from the ECG is connected to the frame grabber. 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. Feature tracking has been proposed as a means of reconstructing the surface viewed through the endoscope and tracking its motion [9].

If corresponding features can be tracked in the left and right views through the da Vinci stereo-endoscope, these 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 present of rigid motion of the camera or near rigid motion due to breathing.

Having established temporal registration, the remaining motion will be rigid apart from possible deformation of the heart due to breathing. Preliminary work has shown that 3D-3D non-rigid registration can be used to build separate models of respiratory motion of the liver [10] and heart [11]. Since both respiratory and cardiac motion are smooth and continuous, we will develop 4D parametric motion models based on 4D B-splines. These motion models will provide compact representations of cardiac motions.

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 can be developed. We are using the concept of photo- consistency [12,13] as a similarity measure using the calibrated stereo views that are available on the da Vinci system. It is hoped that a combination of these techniques will be able to provide alignment of the 4D model from the cardiac CT images with the series of 2D video images grabbed through the endoscope.

2.3 Visualisation

The da Vinci system provides the surgeon with endoscopic stereo video images of the surgical scene during coronary artery bypass. The goal of this step is to provide an augmented reality facility for the da Vinci system during this procedure.

In order to achieve this 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). Since the intrinsic parameters describe the internal properties of the stereo endoscopic cameras of the da Vinci system, we use an offline camera calibration technique to determine these parameters [14,15].

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. The resulting visualisation will be able to guide the surgeon during critical parts of the procedure.

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. To produce a 4D model we segment the first phase by hand and propagate this to the other 19 phases by non-rigid registration [8]. This is similar to the method used by Szpala et al [5], but here it is demonstrated on clinical coronary CT scans rather than phantom data. Figure 4 gives an idea of the quality of the registration.

In figure 5 we the heart and breathing frequencies, needed as parameters for the 4D model.

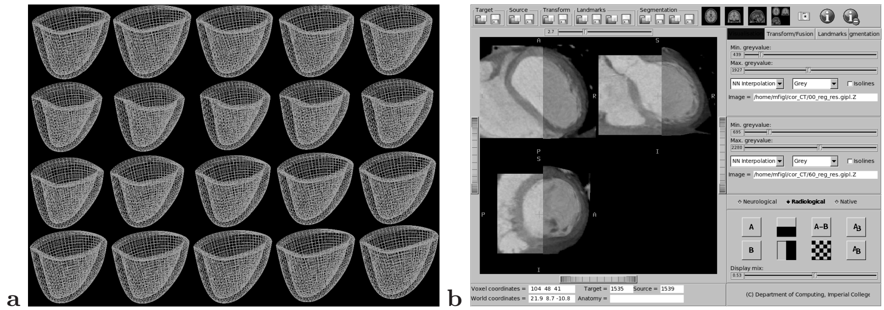

Fig. 4. Non-rigid registration was used to register the first image to the other images. In **a** the deformation of the ventricle is displayed. **b** shows the registered image slices from different phases (0% and 60 %) of the cardiac cycle.

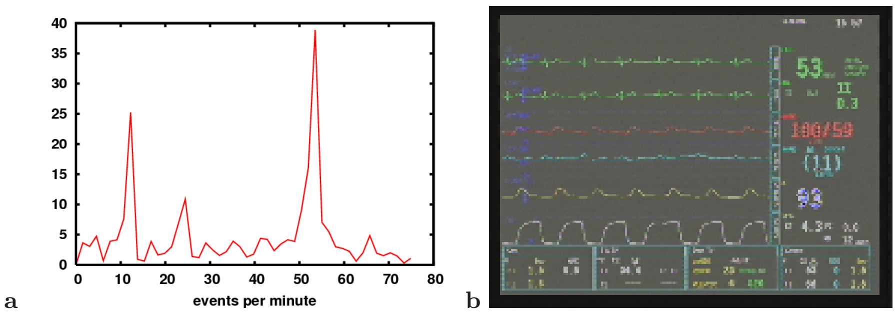

Fig. 5. **a** shows the Fourier transform of the cross-correlation from the image number 12 to the other images of a video sequence of the beating heart like 6 **c**. Two main frequencies can be seen 12 and 54 beats per minute, breathing and the heart beat. **b** shows the corresponding ECG display grabbed with the frame grabber.

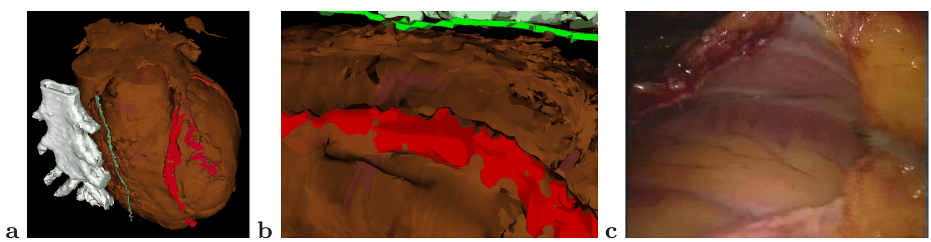

Fig. 6. A rendering of the preoperative model showing the myocardial surface, left internal mammary artery, left anterior descending artery and a diagonal branch (a), an aligned rendering (b) and its corresponding endoscope view (c)

3.2 Visualisation

An example of retrospectively aligned images is shown in figure 6. 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 [5]. Falk et al have demonstrated a system for AR guidance based on multi-planar x-ray angiography [16]. We describe the first such results using clinical coronary CT scans to provide the 4D patient model using non-rigid registration. We 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.

For augmentation of the endoscopic view we use video mixers, which does not introduce any lag to the surgeons view of the real surface. We use chroma-keying for the image fusion, which limits the range of available colours. This is not a significant limitation as we want colour separation between the overlaid view and the largely red surgical view. 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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