SPATIAL COMPOUNDING OF TRANS-ESOPHAGEAL ECHO VOLUMES USING X-RAY PROBE TRACKING

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ABSTRACT

The use of ultrasound imaging for image guidance of cardiac procedures is limited by the small field of view of the ultrasound volume. A larger view can be created by image-based registration of partially overlapping volumes, but automatic registration often fails unless the volume alignment is initialised close to the volumes' correct alignment. In this paper, we use X-ray images to track a trans-esophageal probe, which provides the required position estimates for the ultrasound volumes. The tracking is possible using multiple X-rays or just one X-ray at each probe position. We test the method in a phantom experiment and find that with at least 50% volume overlap, 98% of ultrasound volume pairs are correctly registered when tracked using three X-rays per volume, and 95% using single X-rays.

***Index Terms*—** Registration, compounding, extended field of view, probe tracking, trans-esophageal ultrasound

1. INTRODUCTION

Minimally-invasive cardiac surgical procedures are becoming increasingly feasible with developments in image guidance [1]. Ultrasound is a low cost, non-irradiating, real-time imaging modality, and with the development of two-dimensional (2D) array transducers, has the particular advantage of providing real-time 4D images of the beating heart. Trans-esophageal echo (TEE) imaging allows an ultrasound probe to be placed close to the heart, which minimises the distance travelled by the ultrasound waves. Compared to the alternative trans-thoracic approach, TEE produces less attenuated, higher resolution images, with an unobstructed view of the heart [2].

However, compared to other imaging modalities, an ultrasound transducer images a relatively small cone-shaped volume that is only a few centimetres wide close to the transducer. This is a particular problem for TEE imaging, where the probe is close to the heart and the limited field of view is unable to image the whole heart at once. A larger view can be created by stitching together multiple, partially overlapping volumes, but this requires that the location of each volume is known relative to the other volumes.

Previous work on echo volume compounding has taken two distinct approaches to volume location: probe tracking and image registration. A tracking device attached to the probe can be used to locate each volume. Use of an optical tracking device, as in [3], is not feasible for TEE because it requires a clear line of sight between the probe and the tracking system, whereas a magnetic tracking device [4, 5] could potentially be integrated with the probe. Alternatively, relative volume locations can be determined using image-based registration in the overlapping regions of the volumes [6, 7, 8].

Typically, registration of volumes taken with the probe in different positions is prone to failure due to the optimisation algorithm finding a local rather than a global optimum. The registration algorithm must be initialised with an estimate of the correct transformation to ensure robust registration. This can be obtained by, for example, using anatomical features as landmarks [6] or using a probe tracking device [8].

Here, we are specifically concerned with TEE imaging. During a clinical procedure, TEE is most commonly used in conjunction with X-ray fluoroscopy and the TEE probe is clearly visible in the X-ray image (an example is shown in Figure 1(a)). The X-ray images can therefore be used to locate the probe in the fixed X-ray coordinate system. In this paper, we propose to use this X-ray probe tracking to initialise an image-based registration of a pair of ultrasound volumes. Our method works with multiple X-rays or just one X-ray per volume. We evaluate the method in terms of the proportion of volume pairs successfully registered and show that probe tracking in this way improves the capture range of automatic image-based registration of ultrasound volumes.

2. METHODS

2.1. X-ray probe tracking

The probe head is located in X-ray coordinates using an established probe tracking method. Details of the method can be found in [9]. The method uses 3D-2D registration to locate a 3D nano-CT model of the TEE probe head (shown in Figure 1(b)) to its projection in the X-ray image (Fig. 1(c)). This

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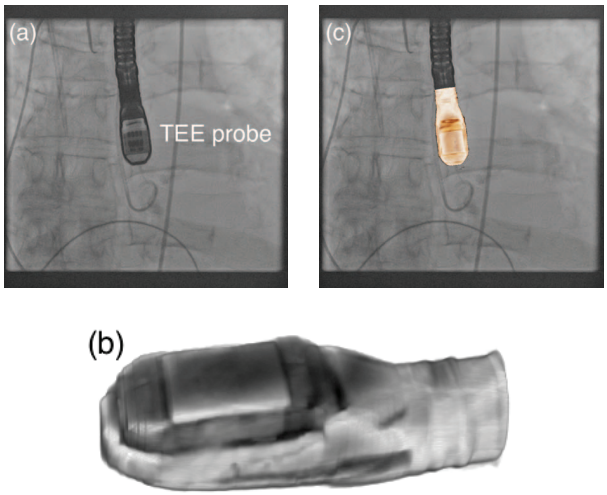


Fig. 1. **X-ray fluoroscopy image**. (a) X-ray image from an aortic valve replacement procedure. The TEE probe is clearly visible. (b) Probe head model derived from a high-resolution CT image. (c) The probe model is registered to the X-ray image using 3D-2D registration.

provides both the position and orientation of the probe head in the fixed coordinates of the X-ray system.

Given a single X-ray view, this registration is accurate only in the plane of the X-ray and the probe may be significantly misplaced along the X-ray projection line. To overcome this, we must take more than one X-ray, from different directions, and locate the probe at the intersection of the projection lines. The orientation is then taken as the average of the individual orientations. In the absence of a bi-plane X-ray system, multiple views are obtained sequentially without moving the probe.

2.2. Registration initialisation

In this paper, we consider three approaches to initialisation. The first is to take three X-rays from different directions for each echo volume. This provides a probe location in X-ray coordinates, accurate in all six degrees of freedom, $T_{xray \leftarrow probe}$, which is converted to a volume location via a pre-calculated calibration, $T_{probe \leftarrow vol}$:

$$T_{xray \leftarrow vol} = T_{xray \leftarrow probe} T_{probe \leftarrow vol}$$

The initial registration transformation from volume 0 to volume 1, $T_{vol_0 \leftarrow vol_1}$, is simply

$$T_{vol_0 \leftarrow vol_1} = T^{-1}_{xray \leftarrow vol_0} T_{xray \leftarrow vol_1}$$

The second approach to initialisation is to locate the first echo volume using three X-rays, but then use just one X-ray for subsequent volumes. The single X-ray gives partial information about the probe position, locating it to a projection line. We then take the nearest point on the current projection line to the previously found probe position. This assumes that the probe will not have moved much in the X-ray's out-of-plane direction. This is a reasonable assumption, given that the probe is constrained inside the esophagus.

Finally, we consider the case of having no X-ray data available. In this situation, we initialise assuming that the probe has not moved between volumes.

2.3. Image registration

Starting from the initial location estimates, volumes are aligned in a rigid, six degree-of-freedom registration. Depending on the initialisation method, we can further refine the initialisation prior to the six degree-of-freedom registration by an exhaustive search over a few of the degrees of freedom. This is potentially slow, but we can do a coarse search in up to three degrees of freedom in a few seconds.

Since the X-rays track the location of the probe, rather than the volume, small errors in orientation tracking can significantly misalign the echo volumes. Therefore, when initialising with multiple X-rays, we do this initial search over the three orientation degrees of freedom. The search range is $\pm 15^\circ$ in steps of 7.5°, giving a total of 125 search locations. When tracking using a single X-ray, we must also consider the projection line error. In this case, we search along the projection line (± 20 mm in steps of 5 mm) and two of the orientation degrees of freedom (225 search locations). We do not search over orientations in the plane of the X-ray, because we expect this to be the most accurate of the three orientation angles in the 3D-2D probe to X-ray registration. Having refined the probe tracking initialisations in this way, we then use a simple downhill optimisation method to locate the volume in all six degrees of freedom.

The similarity measure is the phase-based measure previously developed in [6]. This uses a monogenic signal to generate phase and orientation images. This information is invariant to contrast variations and so is well suited to ultrasound registration. For the registration only, the original images are resampled to 2 mm voxels and filtered by a bandpass log-Gabor filter centred on features of wavelength 20 mm.

3. EXPERIMENTS

3.1. Data acquisition

Data to test the registration were acquired from the ultrasound heart phantom shown in Figure 2 (Model 067, CIRS, Virginia, USA). The phantom construction meant that the ultrasound probe imaged it from the front of the heart, which is an unrealistic position for a TEE scan. However, the resulting images contained appropriate features for registration and so were suitable data to test our registration technique. To realistically represent the constraints of the esophagus, the neck of the TEE probe was inside a fixed tube (see Figure 2). Probe

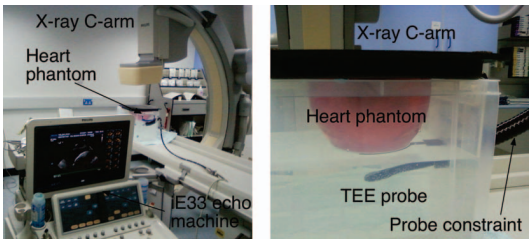


Fig. 2. **Experimental setup**. The heart phantom was placed upside down in a water tank and was scanned from below by the TEE probe.

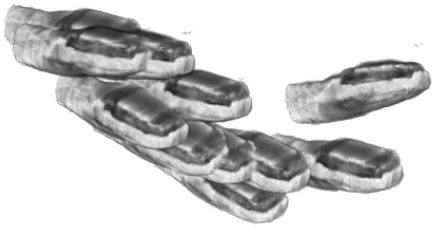


Fig. 3. **Probe positions**. These are the approximate relative probe positions for the 11 acquired volumes derived from multiplane X-ray probe tracking.

movements between volumes were mainly translations along the length and rotations about the axis of the tube.

We acquired the ultrasound volumes with a Philips iE33 3D ultrasound system with an X7-2t 3D TEE probe. 11 volumes were acquired with the ultrasound scanner in Full Volume mode. Each volume had a depth of 15 cm, and produced a voxel array of $17.1 \times 18.7 \times 15.1\,\mathrm{cm}^3$ with voxel resolution $0.82 \times 0.83 \times 0.73\,\mathrm{mm}^3$. In each probe position, three X-ray images were acquired using a Philips Allura Xper FD10 C-arm system, with the C-arm in LAO 45, PA and RAO 45 positions. Figure 3 shows the 11 probe positions determined from the multiplane X-ray probe tracking technique.

3.2. Registration robustness

In this paper, we are primarily interested in how different initialisation methods affect the success rate of the ultrasound registration. The large volume size means that all volume pairs overlap to some extent, so we consider every possible pair of volumes (110 pairs in total). Each volume pair was registered using each of the three initialisation methods: three X-rays, one X-ray (PA view) or no X-rays. Success or failure for each registration was determined by visually examining the overlap region of the registered pair. Correct registration aligned image features to within 5 mm error. This is derived from the size of the smallest structures of interest in the heart, such as the pulmonary veins (>10 mm diameter). Incorrect registrations had much larger misalignments in both position

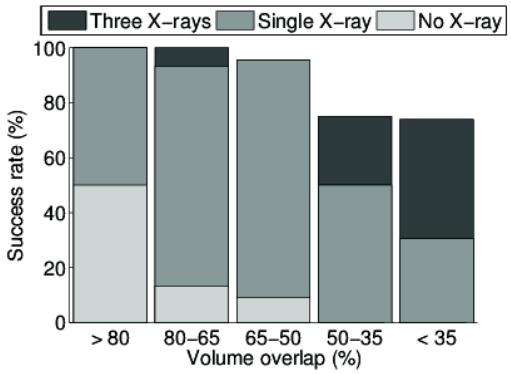


Fig. 4. **Success rate of registration**. The success rate for three X-rays in the >80% and the 65–50% ranges are the same as for the single X-ray method. With no X-rays, It is 0% for overlaps of less than 50%.

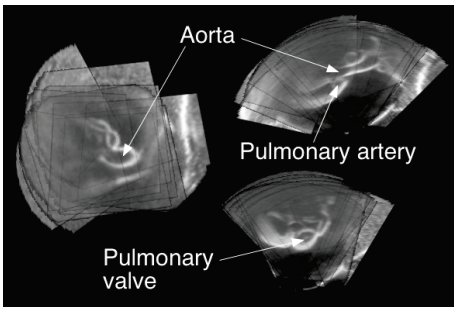


Fig. 5. **Compounded view**. The images are sections through the extended volume showing part of the phantom's heart structure. The curved phantom surface is visible over several volumes at the bottom of the figure.

and orientation. Each volume pair was assigned a value representing their overlap as a percentage of the maximum overlap. This value varies with both translation and rotation of the probe. The set of overlap values was divided into the following ranges: >80%, 80–65%, 65–50%, 50–35% and <35%. We then measured the fraction of successful registrations in each range and for each initialisation method.

4. RESULTS AND DISCUSSION

The overall number of successful registrations for the 110 volume pairs was 97 (88%) for the three X-ray initialisation, 78 (71%) for the single X-ray initialisation and 10 (9%) with no initialisation. Figure 4 shows how the success rate depends on the separation of the volumes. The final compounded image, using all 11 volumes, is shown in Figure 5. The compounded image shows an extended view of part of the phantom's heart structure and also the phantom surface close to the probe.

From the success rate results, it is clear that some kind of

probe tracking is essential for a robust registration of partially overlapping volumes. With no initialisation almost all registrations failed, even when the volumes were close together. In comparison, X-ray probe tracking raises the success rate significantly, with 100% success for greater than 65% overlap when using multiple X-rays for initialisation, and greater than 80% overlap using single X-rays. For smaller overlaps (>50%), the success rate for single X-rays is 95%, which compares well to 98% for multiple X-rays. The few failed cases using three X-rays mostly involve two of the 11 volumes that have a large discrepancy between the correct alignment and the initialisation position obtained from the X-rays. This is perhaps because the probe was not perfectly stationary during acquisition of these volumes.

It is an important result that there is a high success rate using single X-rays. Taking fewer X-ray images is always better since it minimises the radiation dose given to the patient. Also, it simplifies the acquisition protocol using a mono-plane X-ray system, as the C-arm does not need to be moved to different positions while acquiring the sequence of volumes. A possible acquisition protocol would be to register most volumes using a single X-ray, but with the option of acquiring more X-rays if the registration fails.

It is not surprising that volumes with more overlap can be registered more reliably. This is partly because of the amount of information available in the overlap region, but also because the assumptions in the initialisation become less valid at larger separations. Specifically, the assumption used for single X-ray tracking of only small movements in the X-ray's out-of-plane direction is less likely to be true. The results show that using X-ray tracking increases the capture range of the registration, allowing the volumes to be registered with less overlap. Eventually, our objective will be to acquire images covering a region of interest with as few volumes as possible. The improved capture range provided by X-ray probe tracking allows a region to be covered by fewer volumes.

A further advantage of probe tracking in this way is that the extended field of view image is located in X-ray coordinates, rather than an arbitrary coordinate system. This potentially allows the compounded echo image to be combined with X-ray for image guidance in the same way that pre-procedure CT or MR images are currently used [1].

5. CONCLUSIONS

In this paper, we have proposed and tested a method for initialising image-based registration of echo volumes by tracking the ultrasound probe in X-ray images. The probe can be tracked using multiple X-rays or just a single X-ray per volume, with very few failed registrations in either case when the volumes overlap by more than 50%. This tracking allows the creation of extended field of view images by the image-based registration of volumes that are only partially overlapping. In future work, we intend to test our methods on clinical scans, in which cardiac and respiratory motion provide an additional challenge to accurate registration initialisation.

6. REFERENCES

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