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Intraoperative Registration of Preoperative 4D Cardiac Anatomy with Real-time MR Images

Xifeng Gao*, Nikhil V. Navkar*†, Dipan J. Shah‡, Nikolaos V. Tsekos† and Zhigang Deng*
*Computer Graphics and Interactive Media Lab, and †Medical Robotics Lab,
Department of Computer Science, University of Houston, Houston, TX 77004, USA.
Email: gxf.xisha@gmail.com,{nvnavkar, ntsekos, zdeng}@cs.uh.edu
‡Methodist DeBakey Heart & Vascular Center, Houston, TX 77004, USA. Email: djshah@tmhs.org

***Abstract*—Co-registering pre- and intra- operative MR data is an important yet challenging problem due to different acquisition parameters, resolutions, and plane orientations. Despite its importance, previous approaches are often computationally intensive and thus cannot be employed in real-time. In this paper, a novel three-step approach is proposed to dynamically register pre-operative 4D MR data with intra-operative 2D RT-MRI to guide intracardiac procedures. Specifically, a novel preparatory step, executed in the pre-operative phase, is introduced to generate bridging information that can be used to significantly speed up the on-the-fly registration in the intra-operative procedure. Our experimental results demonstrate an accuracy of 0.42mm and a processing speed of 26 FPS of the proposed approach on an off-the-shelf PC. This approach, is in particularly developed for performing intra-cardiac procedures with real-time MR guidance.**

Index Terms*—*Intra-operative Registration, Cardiac Surgery, 4D Mesh Models, and Real-time MR.

I. INTRODUCTION

Continuous advancement in real-time magnetic resonance imaging (RT-MRI) has attracted a growing interest of using the modality for intraoperative guidance of interventions on the beating heart, such as stem cell therapy and valvuloplasties [8], [3], [9], [5]. Use of intraoperative RT-MRI is a challenging task. First, current state-of-art RT-MRI can collect dynamic images at a rate of 20-25 Hz (i.e., 40-50 ms/image) and practically one or two oblique 2D images can be collected to maintain a high refreshing ratio of visualizing the beating heart. Second, due to the limited speed of the modality, 3D/4D, high resolution and contrast images of the heart (e.g., the traditional CINE that requires breath-holding) can only be collected pre-operatively, or if needed intra-operatively, the procedure must be interrupted. In either case, it is desired the co-registration of the RT-MRI with the 3D/4D MRI [12]. This situation is also encountered when different modalities are used for diagnosis and guiding a procedure [4].

Delivering high-quality dynamic 3D models based on real-time acquired patient data to the operating room is of paramount importance to guide the high-precision minimally invasive cardiac procedures [3]. To achieve this, several groundbreaking methods have been proposed to dynamically update 3D environments with real-time 2D or 3D imaging with a lower resolution. For example, Smolikova et al. [12] register RT-MRI with a single-cardiac-phase, pre-operative 3D set; but this registration cannot work in real-time. Huang et al. [4] use electrocardiogram (ECG) signals and a spatial tracking system for intra-operative registration of 3D ultrasound (3D US) to pre-operative 4D MRI. To dynamically overlay a pre-operative mesh to intra-operative 2D fluoroscopy, the work of [9] needs users to manually trace landmarks on the pre-operative data. Machine learning techniques have also been employed (e.g., [3]) to fuse pre- and intra-operative data by jointly estimating anatomical models from multiple imaging modalities. However, this approach is computationally intensive and cannot be used in real-time. An intensity-based registration algorithm proposed by Sun et al. [10] align the ultrasound images with pre-operative images, which needs manual interactions to provide an initial alignment. By combining a pre-operative, subject-specific heart model with the tracked 2D trans-esophageal echocardiography (TEE), Cristian et al. [6] describe a method to interactively define and describe the intra-operative mitral valve annulus within the intra-operative subject space.

Co-registering pre- and intra- operative MR is challenging, because: (a) the two data sets have different spatial resolutions and plane orientations, and (b) pre-operative MR data is usually collected with cardiac triggering and breath-holding (i.e., CINE), while RT-MRI is acquired without cardiac triggering and with free-breathing. Although a number of approaches have been proposed to tackle this co-registration problem as an offline process [3], [9], [5], [6], [10], [4], [12], on-the-fly co-registration (i.e., less than 40 ms per RT-MRI image) has not yet been reported to date.

In this work, we propose an approach to dynamically register pre-operative 4D MR data with intra-operative 2D RT-MRI to guide intracardiac procedures. To achieve this aim, we introduce a novel preparatory step, executed in the pre-operative phase, that generates bridging information that can be used to speed up the on-the-fly registration in the intra-operative procedure. The introduced preparation step can substantially accelerate the on-the-fly registration; our experimental results demonstrate an accuracy of 0.42mm and a processing speed of 26 FPS on an off-the-shelf PC.

II. METHODOLOGY

Our proposed method uses three sets of MR data collected pre- and intra-operatively: (i) A *pre-operative CINE dataset*

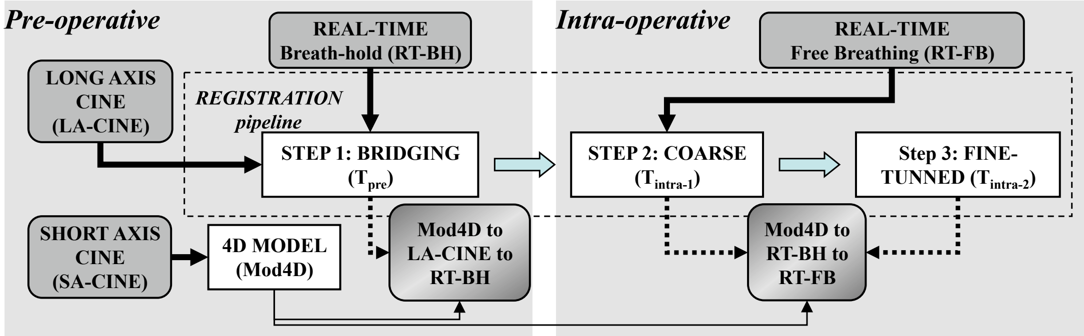


Fig. 1. Pipeline of the proposed pre- and intra- operative MR registration approach.

with a high spatial and temporal resolution was collected with a true fast imaging, stead-state precession (TrueFISP) pulse sequence (iPAT, segment temporal resolution = 39 ms, TE = 1.27 ms, flip angle = 82°, slice thickness = 4.0mm, matrix = 200×256, pixel = 1.56×1.56 mm^2, and 20 frames per cardiac cycle). In this dataset, 19 short axis CINE slices (SA-CINE) were collected to construct the 4D model (denoted as **Mod4D**), and long axis CINE slices (**LA-CINE**) were collected for the first registration step. (ii) A *pre-operative RT-MRI bridging dataset* (denoted as the **RT-BH** dataset), with a high temporal but low spatial resolution which is the best resolution we could achieve for real-time imaging (time per image = 45.6 ms, TE = 0.98 ms, flip angle = 71°, slice = 8.0mm, matrix = 176×110, and pixel = 2.27×2.27 mm^2), was collected without cardiac triggering and breath-hold. Up to 420 frames of RT-BH were collected on each subject. Since this dataset is registered with the above CINE dataset, we only use a group of RT-BH frames that span one cardiac cycle. (iii) An *intra-operative RT-MRI dataset* (denoted as the **RT-FB** dataset) was collected with the same acquisition parameters as RT-BH, without cardiac triggering and with free breathing. We select the LA slice in the above three cases (i), (ii), and (iii) because of the following two reasons: 1) based on the analysis in [15], to minimize differences between the RT-BH and RT-FB sets so that the heart mainly translates along and rotates around without significant out-of-plane motion, 2) to perform coarse registration in Section C, we need extract boundary points from long-axis images.All the datasets were acquired on healthy volunteers (n=3) using a clinic 1.5T Siemens Avanto MR scanner.

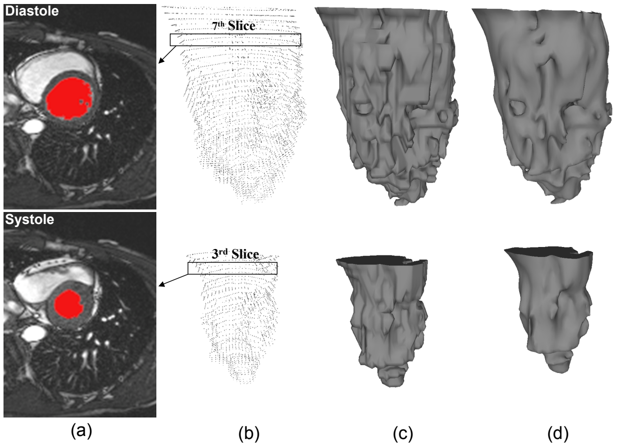
The goal of this work is to dynamically register the above RT-FB dataset with the Mod4D model that is reconstructed from the above pre-operative CINE dataset. The flowchart in Fig. 1 delineates the three tasks of the proposed approach. In the **pre-operative phase**, two tasks are performed. First, a 4D mesh model (Mod4D) of the beating left ventricle (LV) is reconstructed from the SA-CINE dataset. Second, the LA-CINE data is registered to the pre-operative bridging dataset, RT-BH, by computing a rigid transformation, T_{pre}. Note that with T_{pre}, RT-BH is also registered with the Mod4D via LA-CINE. In the **intra-operative phase**, RT-BH is registered, frame-by-frame, to RT-FB. This intra-operative registration is performed in a two-phase protocol: (i) A coarse registration between RT-BH and RT-FB is performed by the iterative closest point (ICP) algorithm [1], which outputs a transformation $T_{intra-1}$. (ii) A fine registration is further performed by a scaled least square cost function (SLS) [14], which produces a transformation $T_{intra-2}$. To the end, the combination of the three produced transformations is able to dynamically register the RT-FB with the pre-operative Mod4D model, that is, $Mod4D_{intra} = T_{intra-2} \times T_{intra-1} \times T_{pre} \times Mod4D$.

A. Construction of Pre-operative 4D Model

The 4D model (i.e., dynamic 3D mesh models) is reconstructed by applying a three-step process to the acquired SA-CINE data (Fig. 2). In the first step, image segmentation (Fig. 2a) is performed by thresholding and a region-growing algorithm (enclosed in the ITK toolkit), followed by an inversion filter to obtain the LV contours (Fig. 2b). The seed points are manually selected on the LV by considering the papillary muscles and chordae tendinae. In the second step, a 3D iso-surface mesh model of the LV (Fig. 2c) is reconstructed from the contours using the marching cube algorithm [7]. In the third step, the dynamic 3D meshes are smoothed by applying the Laplace + Humphrey Classes (Laplace+HC) mesh smoothing algorithm [11], followed by a low pass filter [2], as shown in Fig. 2d. In addition to eliminating noise, the third step marginally shrinks the original meshes, which is useful when it is used to guide an intracardiac procedure (i.e., maintaining a safe distance from the endocardium).

B. Pre-operative Registration

Performing direct registration between the pre-operative CINE dataset and RT-FB is challenging, because: (i) the pre-operative CINE dataset is collected with breathhold but, practically, the intra-operative RT-FB must be collected with free-breathing; (ii) although the same plane orientations can be selected, the breathing motion affects the morphology of the heart; and (iii) the pre-operative CINE dataset is collected with larger acquisition matrices and a higher spatial resolution than RT-FB (e.g., in our studies, 200×256 vs. 176×110 and $1.56 \times 1.56 mm^2$ vs. $2.27 \times 2.27 mm^2$, respectively). We tackle the above challenge by introducing a bridging dataset RT-BH



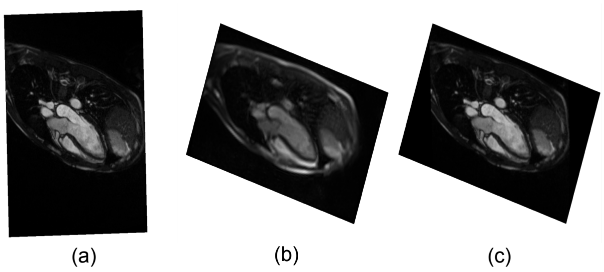

(a) (b) (c)

Fig. 3. Example result from the pre-operative registration (a and b) matched cardiac phases of (a) LA-CINE and (b) RT-BH and (c) interpolated LA-CINE has the same anatomic view as RT-BH.

that is collected with parameters from both sets (i.e., pre- and intra- operative): (i) breath-hold like the pre-operative CINE dataset (isolating the breathing motion), (ii) the same imaging plane orientation as that of the pre-operative LA-CINE, and (iii) the same spatial resolution as that of the intra-operative RT-FB. In the pre-operative registration step, based on the ECG signals (as the phase-stamps), LA-CINE and RT-BH can be accurately identified and paired, as illustrated in Fig. 3(a-b).

The pre-operative registration is performed as follows. First, although the anatomical positions in LA-CINE and RT-BH are very close in 3D coordinate system, due to different employed imaging parameters, their positions in 2D image space could be substantially different. Therefore, to exploit the inherent 3D MR scanner coordinate system, we bilinearly interpolate LA-CINE to generate a copy of LA-CINE that has the same anatomic view as RT-BH (Fig. 3c). Second, to obtain a 2D rigid transformation, we use the ratio image uniformity (RIU) cost function based registration algorithm [13], that uses a multivariate calculus-based minimization procedure [14]. Since all data are at the inherent 3D coordinate system of the MR scanner, it's rather straightforward to get a 3D rigid transformation T_{pre}. When this registration is applied to the RT-BH, the registered 4D mesh models can be computed as:

$$Mod4D_{pre} = T_{pre} \times Mod4D.$$

C. Intra-operative Registration

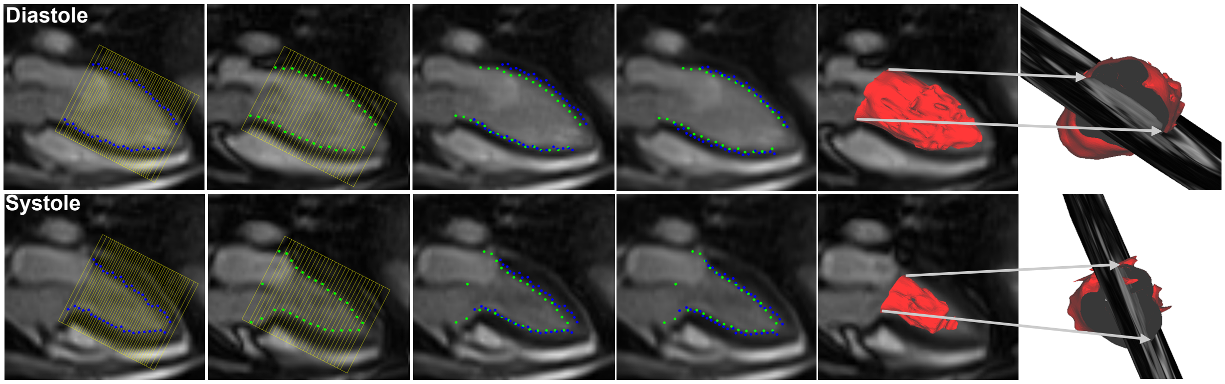
Note that RT-FB and RT-BH are collected with the same imaging parameters (except from the breath-hold). Intra-operatively, the $Mod4D_{pre}$ is updated from the RT-FB frames with a two-steps registration, one coarse and the other for fine-tuning.

Coarse Registration: This step is based on the ICP algorithm [1]. The endocardium is rapidly traced on the RT-BH and RT-FB frames using the boundary point extraction approach proposed by Navkar et al. [8] to generate the P_{bh} and P_{fb}. Fig. 4(a-b) shows examples of the extracted boundary points. Note that the point numbers in P_{bh} and P_{fb} do not need to be the same, as shown in Fig. 4(a-b). As long as P_{bh} and P_{fb} can generally delineate the boundaries (Fig. 4c), by iteratively minimizing the mean-square distance between P_{bh} and P_{fb}, ICP can robustly register RT-BH with RT-FB (Fig. 4d). The reasons are: (i) both RT-BH and RT-FB have the same MR scanning parameters, and (ii) ideally, respiration is the only cause responsible for the difference between RT-BH and RT-FB; therefore, heart locations in RT-BH and RT-FB are close to each other. In other words, P_{bh} and P_{fb} provide a good initial solution for ICP algorithm. In our case, even if several boundary points are not accurately extracted (Fig. 4c), ICP can still register the two curves accurately (Fig. 4d). The resultant transformation from the ICP registration is denoted as $T_{intra-1}$. Note that we can precompute P_{bh} from pre-operative RT-BH to save computational time during intra-operative registration.

Fine-tuned Registration: Although the above ICP registration could provide reasonable registration results, for cardiac procedures which require catheterization and navigation with a sub-millimeter precision (e.g., angioplasty or electrophysiological interventions), a fine-tuned registration is needed to ascertain the accuracy of the registration procedure. Based on the coarse registration result, $T_{intra-1}$, as well as performance comparison among RIU, the lest-squared difference image (LS), and SLS cost functions based registration algorithms [14], we adopt the SLS cost function based registration algorithm to further refine the registration between RT-BH and RT-FB. Similar to the process in Section II-B, an optimized 2D rigid transformation is first obtained and then transformed to a 3D rigid transformation, $T_{intra-2}$ (refer to Fig. 4(e-f)). In sum, during intra-operative procedure, dynamically updated 3D LV models corresponding to 2D RT-FB are computed as: $Mod4D_{intra} = T_{intra-2} \times T_{intra-1} \times Mod4D_{pre}$.

III. EXPERIMENT RESULTS AND ANALYSIS

To evaluate the proposed approach, we measured the computational time and the registration accuracy on healthy volunteers (n=3). Specifically, we compared three registration approaches: (i) **DIRECT**, this is a direct registration of LA-CINE and RT-FB, (ii) **COARSE**, this includes the pre-operative (Section II-B) and the first intra-operative (Section II-C) steps,



(a) RT-BH (b) RT-FB (c) RT-BH & RT-FB (d) RT-BH & RT-FB (e) RT-FB & Model (f) RT-FB & Model

Fig. 4. Step-by-step illustration of intra-operative registration for systole and diastole phases. (a) and (b): boundary point extraction, (c): before the coarse registration, (d) after the coarse registration, (e) and (f): 3D mesh models after fine-tuned registration.

TABLE I
STATISTICS FOR DIRECT, COARSE, AND TWO-STEP REGISTRATIONS FOR THE 3 SUBJECTS

Sequence	Time (ms)			Accuracy (mm)		
	DIRECT	COARSE	TWO-STEP	DIRECT	COARSE	TWO-STEP
#1	604.83±32.12	0.54±0.22	39.62±14.25	0.74±0.21	0.79±0.31	0.47±0.05
#2	622.01±19.43	0.66±0.09	40.92±11.70	0.61±0.37	1.05±0.47	0.45±0.26
#3	587.41± 51.98	0.62±0.048	34.42±7.59	0.44±0.13	0.95±0.37	0.33±0.09

and (iii) **TWO-STEP**, this is the COARSE plus the final intra-operative optimization step (i.e., the complete process). All studies run on a commercial PC (Intel i7 2670QM 2.2GHz CPU; 8GB RAM) and were repeated 50 times for statistical significance. For the registration accuracy, we compared the endocardial boundaries on the matched 4D mesh and RT-FB frames. Specifically, we (i) calculated the intersection line $I(J)$ of the RT-FB and the matched 4D mesh, (ii) manually traced the endocardium $M(J)$ on the corresponding RT-FB, and (iii) calculated the distance between the $I(J)$ and $M(J)$. The manually traced, by two experienced cardiac MR specialists, endocardium on the RT-FB was the ground truth.

Fig. 5 shows the computational times and error for an entire sequence (#1) collected from one volunteer. The average processing time for the TWO-STEP process is 39.62±14.25 ms that is 15.3-times faster than the DIRECT method. In addition, it is in the range of the refreshing rate of the RT-FB (i.e., 48.3 ms/frame); the registration process finishes before the next RT-FB image is collected. The DIRECT, in Figs. 5a and 5d, exhibit two “valleys”; we attributed them to the breathing cycle that at certain periods RT-FB and RT-BH are close to each other. This reduces the computational time for DIRECT, as well as the error. Such “valleys” are not observed in either the COARSE or the TWO-STEP, since the former step makes calculations more consistent. In regard to accuracy, the COARSE exhibits similar results with the DIRECT (Fig. 5d, 0.79±0.31mm vs, 0.74±0.21mm, respectively), while the TWO-STEP better at 0.47±0.05mm.

Table I presents the results from the three subjects. It is noted that the average computational time for n=3 was 38.3 ms achieving an average accuracy of 0.42mm, which is less than 7% of the time and 71% of the accuracy error of the DIRECT registration. The results in Table I, demonstrate that the TWO-STEP clearly outperforms those of the DIRECT approach for all the subjects. It can be concluded that the COARSE step provides a good starting point for the TWO-STEP registration, contributing to a lower probability the latter step stuck to a local minima.

IV. CONCLUSION AND FUTURE WORK

We propose an approach for on-the-fly update of a pre-operative LV 4D model using real-time 2D MR. To accelerate processing, the pre- and intra-operative data are matched based on the collection of an additional set of data and processing at the pre-operative phase. The method achieves a speed as fast as 26 FPS and accuracy of 0.42mm. The application of this method is to guide interventions, and to the best of our knowledge this is the first work that can perform on-the-fly registration. However, we used rigid registration because of (i) the relatively faster speed achieved as compared to that of the non-rigid registration, (ii) the fact that we use the same modality and orientation of the real-time images, and (iii) those of the 20 pre-collected models (heart geometry) are continuous enough to consider the heart still during a single registration phase. Future work will be focused on the use of two to three oblique-to-each-other RT-FB slices to cover more tissue, include patient studies (pending institutional approvals and recruitment) as well as a larger number of healthy volunteers in the near future. In those studies, an important area will be to assess to what degree the method can follow sudden and large changes in morphology (as example with deep and irregular breathing).

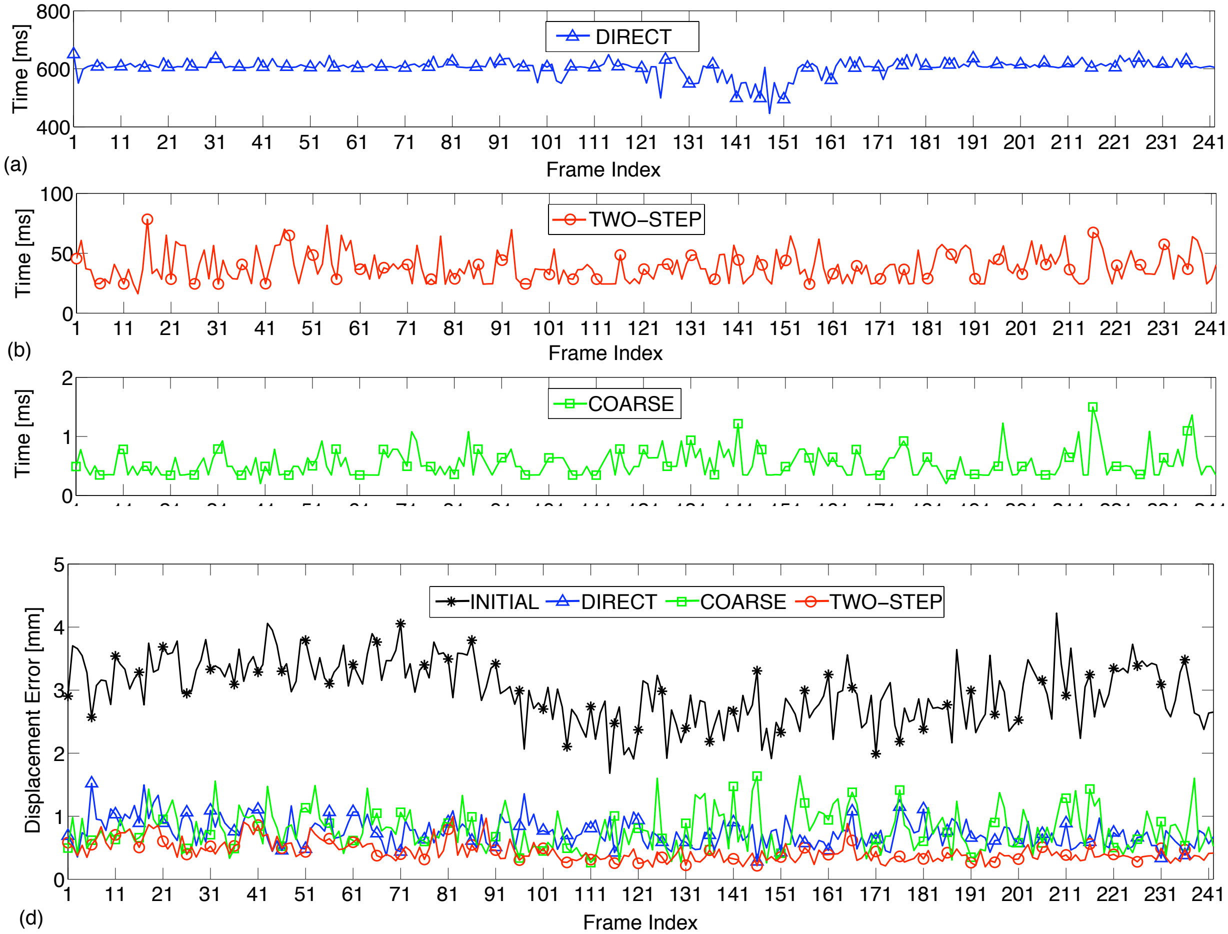


Fig. 5. (a to c) the computation times for an RT-FB sequence #1 (242 frames) measured for completion of (a) DIRECT, (b) COARSE, and (c) TWO-STEP registration performed on sequence #1. (d) Error calculated for the four registration steps for sequence #1(INITIAL: after preoperative registration).

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