Doo-Sabin Surface Models with Biomechanical Constraints for Kalman Filter Based Endocardial Wall Tracking in 3D+T Echocardiography

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3D+T echocardiography is a valuable tool for assessing cardiac function, as it enables real-time, non-invasive and low cost acquisition of volumetric images of the heart. The automated tracking of heart chambers in 3D+T echocardiography remains a challenging task due to reasons including speckle noise, shadowing, and the existence of intra-cavity structures [6]. Furthermore, the real-time detection of endocardial borders might be desirable for the invasive procedures and intensive care applications. State-space analysis using Kalman filtering can be employed for the detection of left ventricle (LV) structures in time-dependent recordings. Orderud et al. proposed a Kalman tracking framework for the real-time detection of LV structures in 3D+T echocardiography [5]. The study took advantage of compact Doo-Sabin model representations for rapid tracking, but it did not utilize physical properties to constrain model deformations. Liu et al. introduced a biomechanical-model constrained state-space analysis framework for the tracking of short-axis 2D+T echocardiography recordings [4]. Their study used *dense* Delaunay triangulated models and employed basic tri-nodal linear elements during the finite element analysis (FEA). Due to triangulated high resolution model representations, it offered a computationally expensive solution.

This paper proposes an approach to combine the compact model representations with biomechanical constraints for rapid and accurate tracking. We extend the real-time Kalman tracking framework described in [5] by employing biomechanically constrained state transitions. First, FEA for the tracked Doo-Sabin surface model is performed using the isoparametric method introduced in [3]. This step enables the computation of a stiffness matrix $\mathbf{K}$ for a given endocardial model using shell elements without changing the model geometry. However, the computed model might lead to inaccurate deformation modes due to hypothesized model shape and FEA parameters (e.g. Young's modulus, Poisson's ratio). Accordingly, we improve the model shape and stiffness matrix using statistical information collected from a training data via Control Point Distribution Models (CPDM) [2]. During the improvement stage, (1) the model shape is updated to the population mean, (2) the stiffness matrix for the updated model shape is computed as $\mathbf{K}'$ (see Figure 1), and (3) $\mathbf{K}'$ is further modified to $\mathbf{K}_{opt}$ to produce similar modes of deformation as the statistically observed ones using Baruch and Bar-Itzhack direct matrix modifications (BBDMM) [1]. Finally, the state prediction stage of the Kalman tracking framework is formulated to perform biomechanically constrained tracking.

In the results section, endocardial surface tracking quality is compared among (1) Doo-Sabin surface models with different control node resolutions, (2) biomechanically constrained and non-constrained state transitions, and (3) the systems employing statistically improved and not improved Doo-Sabin models (see Figure 2). Our analyses showed that

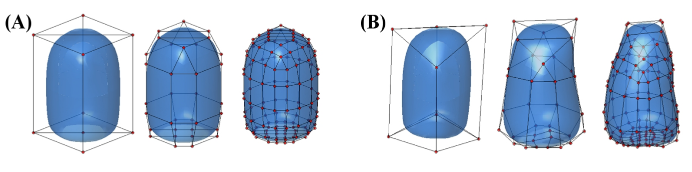

Figure 1: (A) Not-refined, refined and double-refined endocardial Doo-Sabin surface models, and (B) the same surface models after the model shape updates.

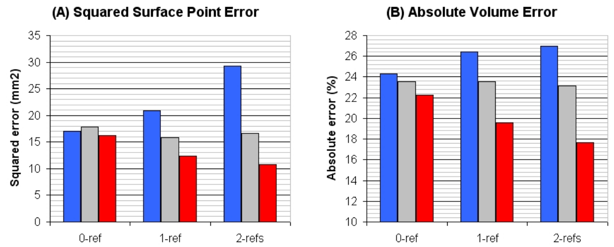

Figure 2: (A) Squared surface point error (in mm^2), and (B) absolute volume error (in percentages) for the Kalman tracking framework using no biomechanical constraints (blue), biomechanical constraints but no statistical improvements (gray), and biomechanical constraints and statistical improvements (red) for non-refined (0-ref), refined (1-ref) and double-refined (2-ref) Doo-Sabin model tracking.

the biomechanical constraints are necessary especially when the tracked model has a high control node resolution. This is due to the fact that as the model complexity increases the tracker can benefit more from a spatial regularization, which is provided by biomechanical constraints. The statistical model improvements take advantage of higher model resolution levels as (1) the model node updates provide a more realistic model shape to perform tracking, and (2) deformation modes learned from CPDM improve the stiffness matrix accuracy. The tracking framework is implemented in C++, and processes each frame in $2ms$ with not-refined (9 control nodes), $3.4ms$ with refined (34 control nodes) and $30.6ms$ with double-refined (136 control nodes) models when executed on a 2.80 GHz Intel Core 2 Duo CPU. The introduced method is (1) practical; the computed models can be directly used in a Kalman tracking framework by implementing a few modifications in the state prediction stage, (2) useful since it improves the tracking accuracy without introducing additional run-time complexity, (3) yet novel as the biomechanically constrained subdivision surfaces have not been employed in a Kalman tracker prior to our study.

[1] M. Baruch and I. Y. Bar Itzhack. Optimal weighted orthogonalization of measured modes. *AIAA Journal*, 16(4):346–351, 1978.

[2] T. F. Cootes, C. J. Taylor, D. H. Cooper, and J. Graham. Training models of shape from sets of examples. In *In Proc. British Machine Vision Conference*, pages 9–18, 1992.

[3] E. Dikici, S. R. Snare, and F. Orderud. Isoparametric finite element analysis for doo-sabin subdivision models. In *Proceedings of Graphics Interface 2012*, GI '12, Toronto, Ont., Canada, Canada, 2012. Canadian Information Processing Society.

[4] Ning Lin, Weichuan Yu, and James S. Duncan. Combinative multi-scale level set framework for echocardiographic image segmentation. *Medical Image Analysis*, 7:529–537, 2002.

[5] F. Orderud and S. I. Rabben. Real-time 3d segmentation of the left ventricle using deformable subdivision surfaces. In *CVPR*, 2008.

[6] S. K. Setarehdan and John J. Soraghan. *Segmentation in echocardiographic images*, pages 64–130. Springer-Verlag New York, Inc., New York, NY, USA, 2002. ISBN 1-85233-389-8.