Quadratic Calibration For The Automatically Computed Boundaries: An Application in X-ray Heart Imaging

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Abstract

This paper describes a calibration procedure to reduce the error of raw automatically produced left ventricle boundary delineations from ventriculargrams. On a data set of 377 patient studies, the algorithm was able to delineate the boundary for the left ventricle with an average error just over 2.4 mm relative to the gold standard of cardiologist hand traced boundaries.

1. Ventriculography

Contrast ventriculography is a procedure routinely performed in clinical practice during cardiac catheterization. Catheters are intravascularly inserted into the heart to inject a contrast dye so that the left ventricle may be more clearly images with X-Rays. The time sequence of such image frames is called a ventriculogram. They constitute a projection image sequence of the endocardial surface of the left ventricle chamber. These images are used to determine the endocardial boundary at the end diastole, when the heart is filled up with blood, and at the end systole, when the heart is at the end of the contraction phase during the cardiac cycle.

We have reported in another paper [2] an automatic approach to determining the boundaries of the left ventricle. We noticed that this automated approach produced boundaries in which the errors in the inferior wall delineation and apical zone delineation were systematic. In this paper we describe the approach we took to calibrating out the systematic shape errors produced by the automatic boundary delineation algorithm using physician specified points for the aortic valve plane and the apex.

2. Calibration methodology

The input raw and ground truth boundaries are initially in an irregularly spaced vertex polygon format with 100 vertices and unit dimensions in millimeters. The polygons are resampled and interpolated into into an appropriate number of equally spaced vertices before it undergoes the calibration procedure discussed below

Fig. 1 shows a typical raw classification boundary for the end diastole and end systole frames of the cardiac cycle. The systematic boundary error cancellation methodology is, in effect, a calibration procedure which calibrates out all systematic position, orientation, and shape errors of the raw classified boundaries like those seen in Fig 1. The calibration transformation is estimated using a database consisting of the ground truth boundaries and the corresponding raw boundaries generated by the classifier.

The cross-validation protocol for estimating the accuracy of the boundary error cancellation procedure takes a database of N patient studies and partitions it into K equal sized subsets. Then for all K *choose* L combinations, the transformation using L subsets is estimated. Now using the estimated transformation on the remaining $K - L$ subsets, the mean error of the transformed boundary is estimated.

3. Performance and data analysis scheme

The error between a computed boundary and the ground truth boundary is defined as the average distance between each vertex of the computed boundary and the polygon of the ground truth boundary and the distance between each vertex of the ground truth boundary and the polygon of the computed boundary.

For each vertex of the boundary, the calibrated

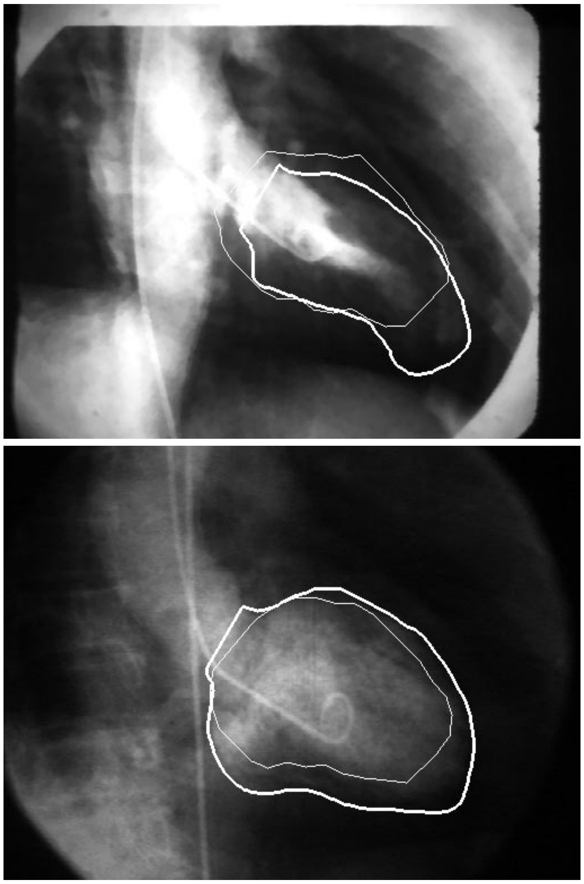


Figure 1. Results of the pixel classification algorithm over ED and ES frames of the cardiac cycle. Top : End Systole (ES) frame showing very little dye in the apex zone of the left ventricle and the pixel classification boundary (the thin boundary line) falls short in the apical zone. Also seen is the over estimation of the inferior walls. Thicker boundaries are the boundaries drawn by the cardiologist. row: End-Diastole (ED) frame showing very little dye in the apex zone of the left ventricle and the pixel classification boundary (the thin boundary line) is under-estimated in the apex zone of the left ventricle. The thick boundary lines represent the boundary of the left ventricle as delineated by the cardiologist.

x-coordinate is computed as the linear combination of raw x- *and* raw y-coordinates of the left ventricle boundary and the x and y coordinate of the three user entered points in all possible combinations up to 2nd order terms: this constitutes 1 zero order term, 6 first order terms, and 21 second order terms. The coefficients associated with the linear combination change for each vertex. And the values of the coefficients are estimated by a least squares regression. The calibrated x and y -coordinate of that vertex is computed with a *different* linear combination of raw x- *and* y-coordinates and the 2nd order terms of the three user-entered points. Let $g_n^{'}$ and $h_n^{'}$ be the row vectors of x- and y-coordinates for any patient n. Let $r_n^{'}$ and $s_n^{'}$ be the row vectors of x- and y-coordinates of the classifier boundary. For the calibrated boundary estimation in ventriculograms we are:

- **Given:** Corresponding ground truth boundaries $\mathbf{R}[N \times 2P]$, classifier boundaries $\mathbf{Q}\,[N \times (2P+28)]$ respectively:

$$\mathbf{R} = \begin{pmatrix} g_1^{'} \; h_1^{'} \\ \cdots \\ g_N^{'} \; h_N^{'} \end{pmatrix} \quad \mathbf{Q} = \begin{pmatrix} r_1^{'} \; s_1^{'} \; t_1^{'} \\ \cdots \\ r_N^{'} \; s_N^{'} \; t_N^{'} \end{pmatrix}$$

  where, $t_1^{'}$ are the 1+6+21 augmented terms coming from the 3 user input points of the first study and $t_N^{'}$ is the 1+6+21 augmented terms coming from the 3 user input points of the N^{th} study.

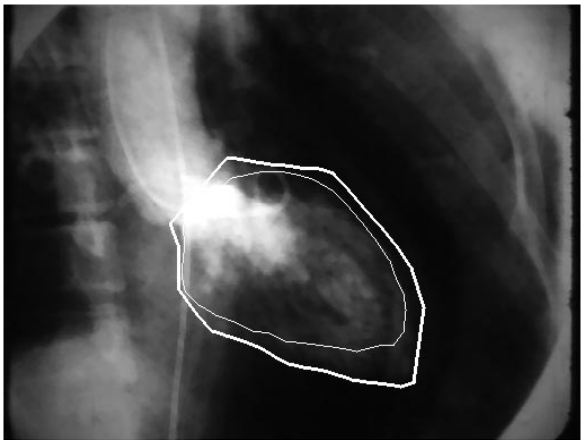
- Let $\mathbf{A}[(2P+28) \times 2P]$ be unknown regression coefficient matrix.

- The problem is to estimate the coefficient matrix $\mathbf{A}$ and to minimize $\| \mathbf{R} - \mathbf{Q}\mathbf{A} \|^2$. Then for any classifier boundary matrix $\mathbf{Q}$, the calibrated vertices of the boundary are given by $\mathbf{Q}\hat{\mathbf{A}}$, where $\hat{\mathbf{A}}$ is the estimated coefficients.

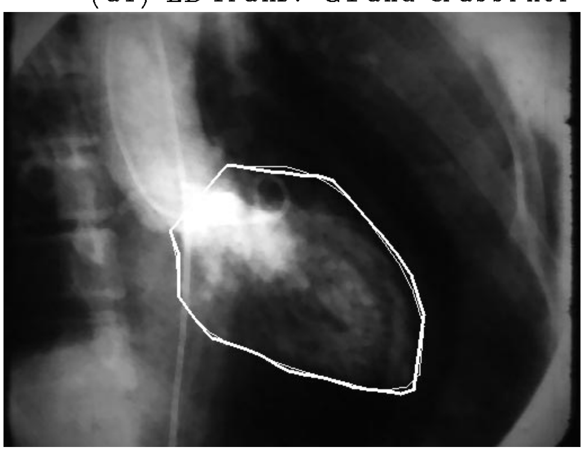
This problem is solved by the standard least squares solution.

Due to the finite number of our patient studies, 377, and the large number of coefficients being estimated, there is a relationship between the number of vertic we sample the polygon and the resulting mean and standard deviation of the boundary error on the test set. If we sample too many points, we in effect memorize the training data and performance on the test set will be poor. If we sample to few points, we do well in terms of generalizing but we incur a large error due to the coarse sampling. Therefore we optimize for the number of vertices. At the optimal values th mean boundary error is just more than 2.4 millimeters.

Figure 2 shows the raw classifier boundary and calibrated boundary for an end diastole frame. Figure 3 shows the same for an end systole frame. The average boundary error for the illustrated examples of Figure 2 and 3 is 2mm



(a1) ED Frame: GT and Classifier



(a2) ED Frame: GT and Estimated

Figure 2. Classifier vs. Estimate ary on End Diastole frame. Thi contour - Ground Truth, Thin LV co Classifier, and Estimated

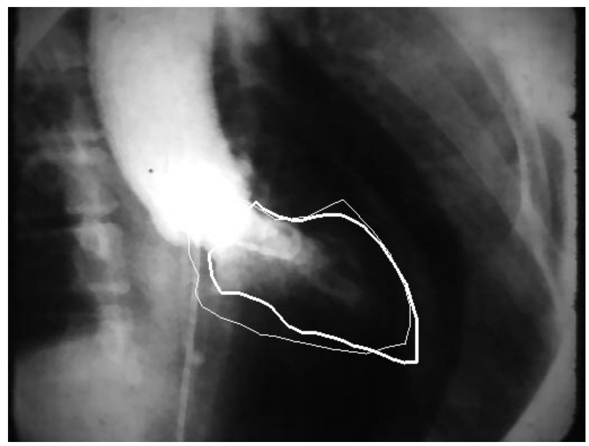
4. Future Work

We are currently examining the errors produced by the algorithm in an attempt to refine it to reduce the average error to less than 2mm. Then we will gather statistics on the ejection fraction estimates that are based on the automatic boundary delineation algorithm

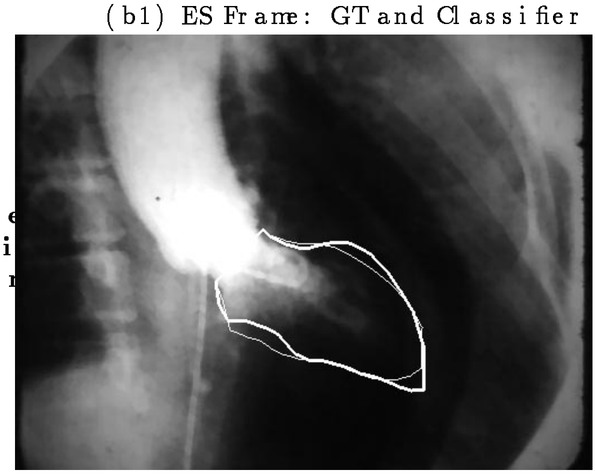
References

[1] Jasjit S. Suri and Robert M. Haralick, "Systematic Error Correction in automatically produced boundaries in Low Contrast Ventriculograms," *International Conference in Pattern Recognition*, Austria, 1996.

[2] Robert M. Haralick, Jas Suri and Florence Sheehan, "Automated Ventriculargram Boundary Delineation," *Bildverarbeitun Fur Die Medizin 1998*, Aachen, Germany, March 26-27, 1998, 1-18, Thomas Lehmann, Voker Metzler, Klaus Spitzer, and Thomas Tolxdorff (ed) Springer-Verlag, Berlin, 1998.



(b1) ES Frame: GT and Classifier



(b2) ES Frame: GT and Estimated

Figure 3. Classifier vs. Estimated bou ary on End Systole frame. Thick LV con tour - Ground Truth, Thin LV contour - Classifier, and Estimated.