Obtaining A New Frame From Each Excitation in Real-Time Acquisitions

U. Sümbül[1], J. M. Santos[1], and J. M. Pauly[1]
[1]Electrical Engineering, Stanford University, Stanford, CA, United States

Introduction: Real-time acquisitions are vital for most cardiac applications. These acquisitions, however, suffer from low SNR and low temporal resolution. Specifically, 20+ frames per second(fps) are often desirable in cardiac imaging, whereas MRI scanners can at most provide raw rates around 10 full fps. Previous works such as the UNFOLD[1] and TSENSE[2] techniques deal with the problem from a Fourier aliasing perspective. UNFOLD performs temporal low-pass filtering, which smoothes the motion of interest and the performance of TSENSE relies additionally on accurately estimating and tracking coil sensitivities[3]. Lastly, these techniques work better on a Cartesian grid. We propose an algorithm exploiting temporal correlations by running a Kalman filter on the raw data. With an *N*-interleaved spiral acquisition, we are able to reconstruct videos running at N times the raw rate, thus revealing a better temporal resolution. Moreover, parallel imaging ability is not compromised, and the reconstruction time is short; the only major components being two gridding and two Fourier transform operations. We compare our algorithm with the sliding window reconstruction, which increases the frame rate by the same amount and provides a rapid reconstruction.

$$S_n = S_{n-1} + U_n$$
$$X_n = \mathcal{G}_n \mathcal{F} S_n + W_n$$

Figure 1 – The Kalman model

Theory: We use the dynamic system given in *Fig. 1* to model the temporal variation of the heart. Here, S_n represents the image at time n, precompensated by the deapodization function, and **F** and $\mathbf{G_n}$ denote the Fourier transform operator and the time-dependent gridding operator, respectively. U_n is the change in the image from time n-1 to n, and W_n is the observation noise with a covariance of $\Sigma=\sigma^2 I$, where I is identity matrix. Both U_n and W_n are modeled as zero-mean random processes. X_n denotes the raw data obtained by one spiral interleaf at time n.

The Kalman filter gives a precise solution to causal filtering of a process based on a finite number of measurements, without assuming stationarity[4]. It is extensively used in tracking applications to get a good estimate from noisy data by utilizing temporal statistics of the dynamic system. We apply the Kalman filter to our imaging model. Since the observations are the raw data obtained by each interleaf, we are able to reconstruct an image from each single interleaf.

Methods: The RTHawk real-time system[5] is used with a gradient-echo pulse sequence and a 4-interleaf bidensity spiral readout. FOV is 20 cm with a resolution of 2 mm. No ECG-gating or breath-holding was used. A small region around the center of the k-space is fully sampled by each interleaf. The covariance matrix of U_n corresponding to the remaining high frequency data is approximately diagonal[6]. This leads to huge computational savings. The very center of the k-space is reconstructed in a conventional way and the remaining part is fed to the Kalman filter. These reconstructions are then combined by simple summation. The statistical estimates required to initialize the filter are obtained by using the full spatial data, where a time window may be used for real-time reconstructions. The noise variance estimate is used as a parameter to trade image denoising for faster tracking.

Results: Several experiments were performed on five volunteers. The imaging slices were chosen to include valve leaflets. The first column of *Fig. 2* shows four consecutive frames obtained by sliding window reconstruction, and the second column shows the corresponding frames obtained by Kalman filtering. These frames capture the valve as it opens up and falls out of the imaging slice. The time between consecutive rows is approximately 21.3 ms.(~ 47 fps) Here, we opted for faster tracking by scaling down the noise variance estimate. Even in this case, the second column has better SNR. Although individual sliding window reconstruction frames appear very acceptable, examining all four frames reveals the temporal low-pass filtering: Differences between the frames are minimal and tracking is sluggish. In contrast, the Kalman frames of the right column show more variations. Since only the raw data coming from a single excitation are used, we obtain better tracking. Lastly, we expect to obtain even better reconstructions as various excitation and reconstruction parameters(flip angle, gradient spoiling cycles, number of interleaves, etc.) are optimized.

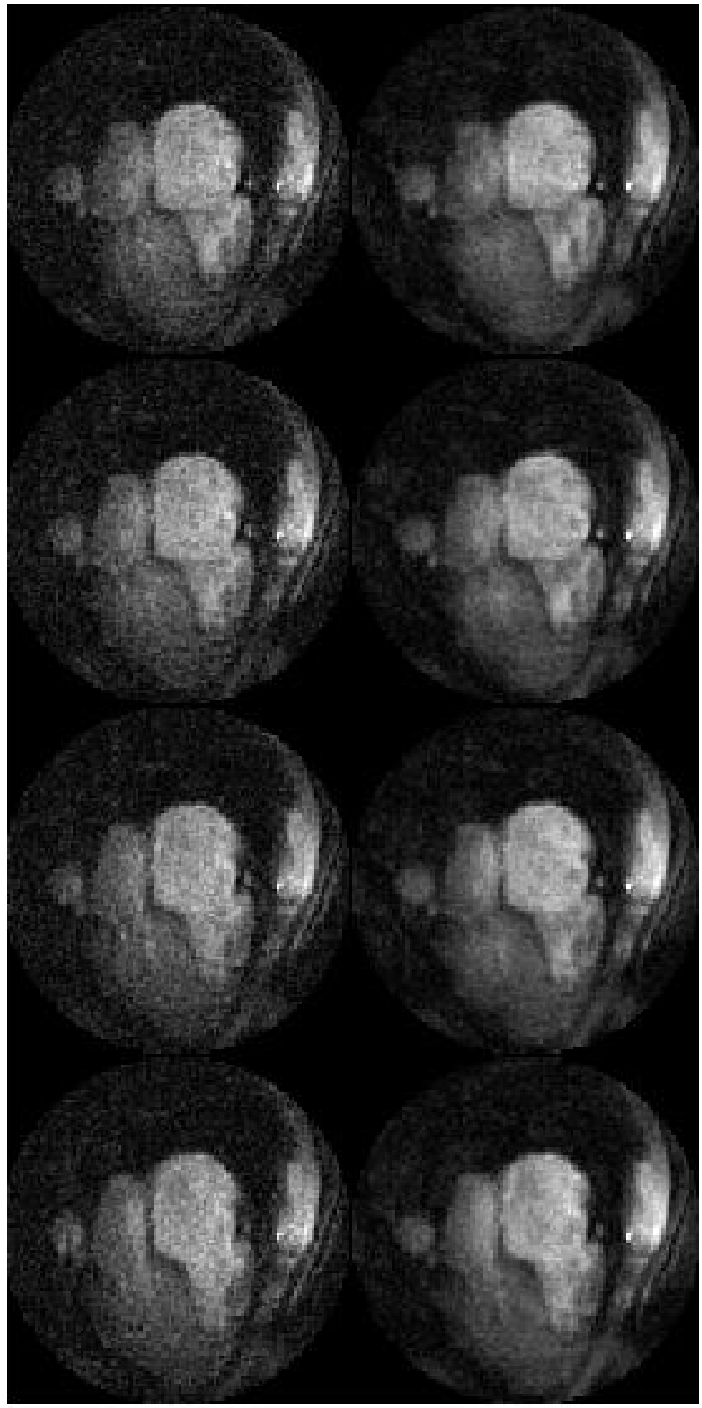

Figure 2 – Four consecutive frames from a cardiac experiment - Left column: Sliding window reconstruction. Right column: Kalman reconstruction

Conclusions: We demonstrated the application of Kalman filtering to real-time acquisitions. Temporal resolution is increased by the number of interleaves and the noise level is decreased as well. Our algorithm has a better temporal response than the sliding window reconstruction. Using raw data coming from only one interleaf allows swifter motion tracking. Our algorithm performs a rapid reconstruction and does not compromise parallel imaging capability.

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