Prospective diaphragm position prediction for Cardiac MR using multiple navigators

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Introduction

Respiratory motion of the heart is a problem for high resolution cardiac MR imaging. Diaphragmatic navigator gating with a 5mm acceptance window is most commonly used to limit this but the technique has an inherently low respiratory efficiency which is further compromised by respiratory drift. Prospective slice following has been implemented [1] to enable larger gating windows and increased respiratory efficiency. This technique uses the navigator position immediately prior to the imaging segment to correct the slice positions throughout the segment. Consequently, the navigator data becomes temporally more outdated as the segment duration increases and the slice following less accurate. We have developed a technique which uses the data from multiple navigators prior to the imaging segment as input data for a predictor estimator, the output of which is the predicted diaphragm position throughout the imaging segment.

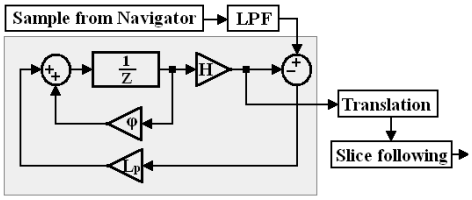
Methodology

The predictor estimator is a control system that compares diaphragm motion to a predefined model and predicts the upcoming state (Figure 1). The plant is sampled periodically and compared to the output of the estimator. The difference between the measured output and the estimated output (the error) is fed back constantly to correct the model to minimize divergence.

First a model of the plant dynamics needs to be constructed. The diaphragm motion is mathematically modelled as a sine wave. Numerous other mathematical models were considered, but were all less accurate and more complex than a single sine wave. The frequency of the model is set equal the breathing rate of the person being scanned. This is determined from a short period of diaphragm monitoring integrated into the start of the scan. The dominant frequency is obtained from the FFT (Fast Fourier Transform) and saved as the model's frequency. The next step in designing the estimator is to place the poles. The poles determine the feedback gain (L_p), which represents how fast the estimator converges to the plant state. Fast poles are used ($Z=0.265 \pm j\ 0.25454$) while the navigators are applied to ensure fast convergence to the plant's state. The system then switches poles for the imaging segments. This effectively sets the error equal to zero and the system completely follows the model. This is done because no samples are available as the navigator is not applied during the imaging segments.

A navigator repeat time of 100 ms is typically used. Because of this rapid repeat time, the navigator signal is noisy and, occasionally, the wrong edge may be output. To minimise this, a low pass filter (LPF) is applied to the navigator signal before being supplied to the estimator. The repeat time of 100ms allows for approximately 5 navigators to be acquired per cardiac cycle prior to the imaging segment (Figure 2). Even though the navigator sampling is only done at a 100 ms period, the output is up sampled to match the echo spacing time in the imaging segment. This is achieved by linearization. The predicted and linearized positions are saved during each cardiac cycle to be accessed for slice following during the imaging segment. The transformation matrix enables scaling to be applied to the output.

Figure 1: Block diagram for predictor estimator
L_p: Feedback gain
Inner loop: Integrator
LPF: Low Pass Filter
Transformation: Matrix for scaling



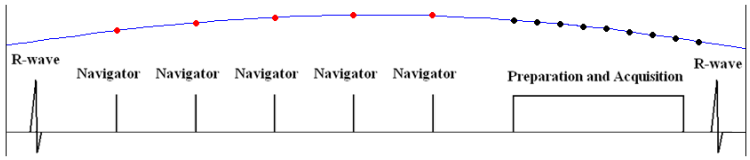


Figure 2. Schematic diagram of one cardiac cycle, red points represent samples obtained from the navigator, the black points represent predicted points

The CV Nav sequence was used as a foundation for implementing the control system. The first navigator is triggered by the ECG and the subsequent navigators followed. After completion of the last navigator, the predicted positions are calculated, up sampled and saved. This does not interfere with the rest of the sequence, as all this is done in the time prior to the imaging segment when the heart is stationary.

The system was initially validated by providing 5 points of a sine wave with a frequency of 14 Hertz. We required the following 5 points to be predicted and followed/predicted without error. The edited CV Nav sequence was used to scan 8 healthy volunteers to validate the system in vivo. The navigator repeat time of 100ms was used in all volunteers and the sequence was set to accept 5 navigator samples and to predict until the next ECG trigger is received. The test was run for 150 seconds with the first 30 seconds not recorded to allow the system to stabilize. Figure3 displays sections of the navigator signal (after being filtered) and the following predictions for two volunteers. To validate the accuracy of the prediction the first Navigator of the next cardiac cycle is compared to the predicted value at that point time. This is the maximum deviation (error) of the predicted values for a given cardiac cycle.

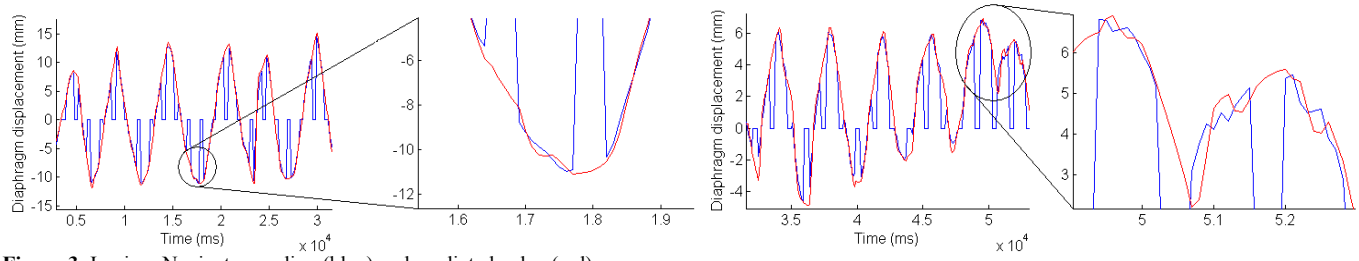


Figure 3: In vivo: Navigator reading (blue) and predicted value (red)

RMS error(mm)	0.6636	0.9441	0.6611	0.5525	0.6229	0.8206	0.7116	0.4873
Diaphragm range(mm)	14.2528	15.58	11.7971	15.216	16.164	17.2655	13.375	12.5345

Table1: Root mean squared (RMS) error and diaphragm range for the 8 volunteers that were scanned

Results

The RMS error of the system compared to the sine wave is negligible (<0.001mm) as would be expected since the system is modelled to a sine wave. The RMS error for all 8 volunteers is presented in table 1. The mean RMS error of the 8 scans is 0.68 mm.

Conclusions

A system has been developed which follows diaphragm motion, as monitored by multiple navigators, and predicts diaphragm position during imaging segments. This could potentially be used to improve the accuracy of prospective slice following and allow a much increased acceptance window and an increased respiratory efficiency.

Reference: [1] Danias P. Radiology 1997;736

Acknowledgments: The South African Research Chairs Initiative of the Department of Science and Technology and National Research Foundation of South Africa, Medical Research Council of South Africa, South Africa / Norway Research Collaboration Programme, and the University of Cape Town.