An Automated Control System for Beat Pilot Tone in MRI

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An Automated Control System for Beat Pilot Tone in MRI

by Jordan Grelling

Research Project

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Approval for the Report and Comprehensive Examination:

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1 Introduction

1.1 Abstract

This thesis will discuss a novel implementation of the Beat Pilot Tone (BPT), a recent technique for measuring the motion of patients during an MRI scan. A pair of pure microwave RF tones generated by an external RF tone generator are transmitted by an antenna inside the bore. The signal is picked up by MRI coils within the bore, and intermodulation at the preamps brings the signal to within the MRI bandwidth to be digitized by the receiver chain. Subject motion modulates the BPT signal which enables motion detection and estimation. The implementation discussed in this thesis aims to connect an external signal generator seamlessly with a GE 3T MRI scanner to automatically collect motion data when requested, allowing technologists to gather motion data without having to calculate appropriate parameters and execute commands on an external device. This is a first step towards using BPT for motion detection and correction in a clinical setting, where it could potentially be used to improve image quality or eliminate breath-holds for many types of MRI pulse sequences.

1.2 Problem Statement

Magnetic Resonance Imaging (MRI) is a powerful medical imaging technique which has become a crucial tool in radiologists' diagnostic arsenals over the past 45 years. Unlike CT, SPECT, and PET, MRI does not subject patients to harmful ionizing radiation, making it a very attractive imaging modality for research. Furthermore, the pulse sequence of magnetic field gradients and radio-frequency (RF) pulses that is applied to acquire an MRI image can be modified to achieve many different types of contrast which provide important physiological information beyond what CT can gather. However, MRI suffers from long scan times per image compared to CT, which can lead to motion artifacts that jeopardize image quality. Bulk motion (the subject switching positions), breathing, and heart rhythms can all lead to motion artifacts, and while these can be ameliorated for certain types of pulse sequences and with specialized equipment, a better way of measuring motion will be critical for future efforts to eliminate motion artifacts in many situations.

2 Background

2.1 NMR Signal

During an MRI scan, a homogeneous magnetic field known as B_0 created by a powerful superconducting magnet aligns nuclear spins in the body. Short radio-frequency (RF) pulses then disrupt the alignment of proton spins in water, which then generate a signal with a frequency proportional to the applied magnetic field as they relax back to equilibrium. This RF signal is received and demodulated, and the subsequent signal corresponds to samples of the spatial frequency domain, known as k-space. [3] An image can be reconstructed by applying an inverse Fourier transform to the sampled k-space.

2.2 Motion Gating in MRI

Accurate motion sensing in MRI is essential to correct for physiological motion that inevitably arises during image acquisition. Conventional motion sensing requires a suite of sensors or sequence-specific changes (e.g. navigators) and can be inconsistent between subjects.

One of the most widely used ways to account for motion in the MRI is known as motion gating. [4] Motion gating uses a secondary signal to measure a heuristic of one dimensional motion over time. This gating signal is then used to separate acquired MRI echoes into separate "bins" depending on the gating signal at acquisition time and reconstruct each bin separately (or throw out the signal from bins unsuitable for reconstruction such as the peak of ventricular contraction in cardiac MRI). The two simplest methods for binning are

Phase binning (typically used for cardiac signals), whereby periodic motion is separated into multiple sequential phases, or amplitude binning (typically used for respiratory signals), where bins are determined by the magnitude of the signal at a given time. In the case of cardiac MRI, this gating signal is most commonly ECG, while for respiratory motion, systems known as bellows or pilot tone are commonly used.

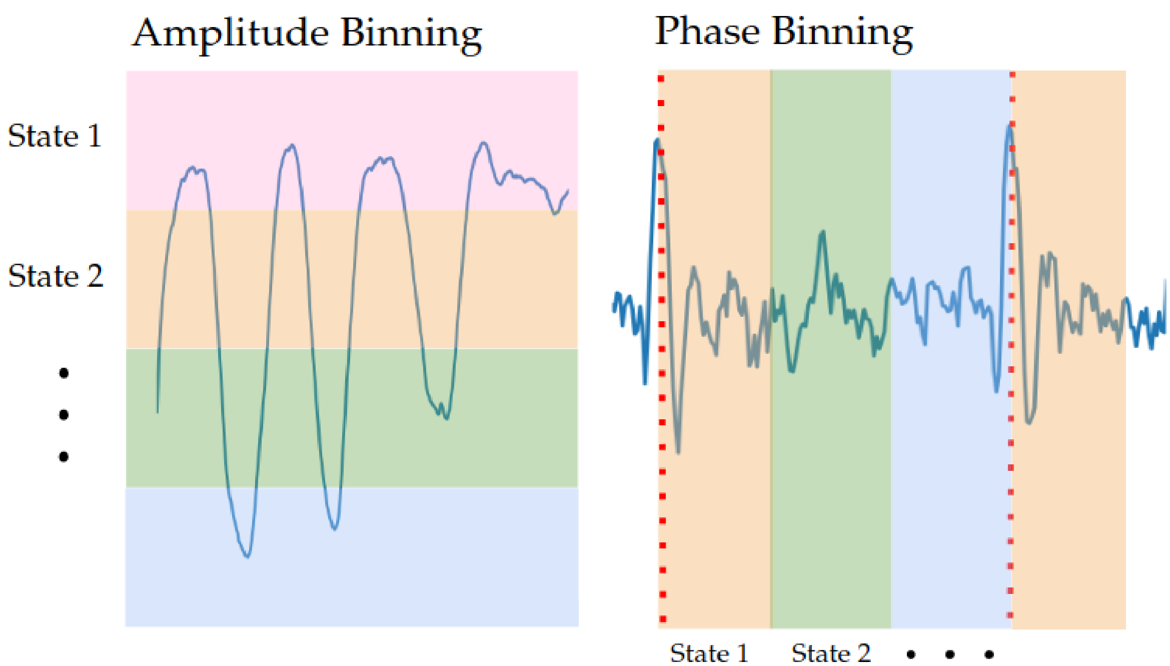

Figure 1: Examples of amplitude and phase binning. Reproduced from [1] with permission by Suma Anand and Katie Lamar.

One of the first such motion sensing methods proven effective is known as a bellows and consists of a belt wrapped around the upper abdomen containing a displacement transducer. [5] Bellows have proven effective at detecting respiratory motion; however, they suffer a variety of drawbacks. First, bellows are designed only to respond to specific types of motion. While respiratory signals are easily detected, bulk motion and vibration cannot be effectively gated.

2.3 Navigator Echoes

Another commonly used motion correction technique is known as a navigator echo. [6] A navigator echo relies on interleaving additional acquisitions with the imaging sequence. These acquisitions do not use phase encoding, so they contain only the 1D Fourier Transform of the image. This navigator acquisition is then cross-correlated with past acquisitions to determine motion along a single axis.

Navigator echoes are effective at correcting for motion; however, they significantly slow scan times due to the need for additional excitations between lines in k-space and are dependent on the sequence being performed.

2.4 Pilot Tone

The Pilot Tone (PT) navigator has been established as a promising alternative to bellows and navigators. [7][8][9][10]. Pilot tones are pure tones broadcast from an external antenna within the MR bandwidth that are modulated by subject position and received by the receiver coils (ie, they occur within the k-space bandwidth of the MRI system). After reconstruction, this tone appears as a line across the image, with its spatial location determined by the distance from the Larmor frequency. Thus, the pilot tone frequency can be set so that it does not overlap with the physiological signal in the imaging FOV. After extracting the magnitude of the PT, we can perform the Fourier Transform of the PT along the phase encode dimension to estimate the relative spatial position of the subject. The PT contains respiratory and cardiac information which can be easily processed from the acquired data [7][8][9][10]; however, the PT frequency needs to be within a narrow bandwidth of the Larmor frequency in order to end up within the receiver bandwidth, and thus can be limited in its sensitivity to subject motion due to the comparatively long wavelength [2]. It does, however, have two advantages over navigator echoes: 1) it can be acquired in parallel with the imaging sequence rather than requiring additional excitations and 2) it is not sequence dependent; the same pilot tone transmission scheme can be used for any pulse sequence.

Pilot Tone also has one additional advantage over bellows and ECG gating, which is that multiple receive coils can be used to fit motion in multiple dimensions. [8] For example, Ludwig et. al. set up the following system of equations:

$$\Delta HF_{reg} = a \cdot PT + b$$

$$\Delta AP_{reg} = m \cdot PT + n$$

Where AP and HF correspond to the motion in the anterior-posterior and head-feet directions. Since the various coils have different sensitivities to each direction, the motion can be modeled to obtain approximate values for displacement in each dimension.

2.5 Beat Pilot Tone

Beat Pilot Tone (BPT) is a recently proposed motion sensing system that aims to ameliorate the low sensitivity of Pilot Tone to motion due to its long wavelength. In Beat Pilot Tone, two ultra-high-frequency RF tones are transmitted, separated by the desired Pilot Tone frequency. [2] These tones are mixed in the preamplification stage via intermodulation to create a beat frequency. [1] We can choose these frequencies such that the received BPT still falls within the imaging bandwidth of the MRI, while maintaining the tissue interaction characteristics of the high frequency RF waves, which have lower permittivity [11] and more noticeable variations in signal amplitude depending on motion state [2].

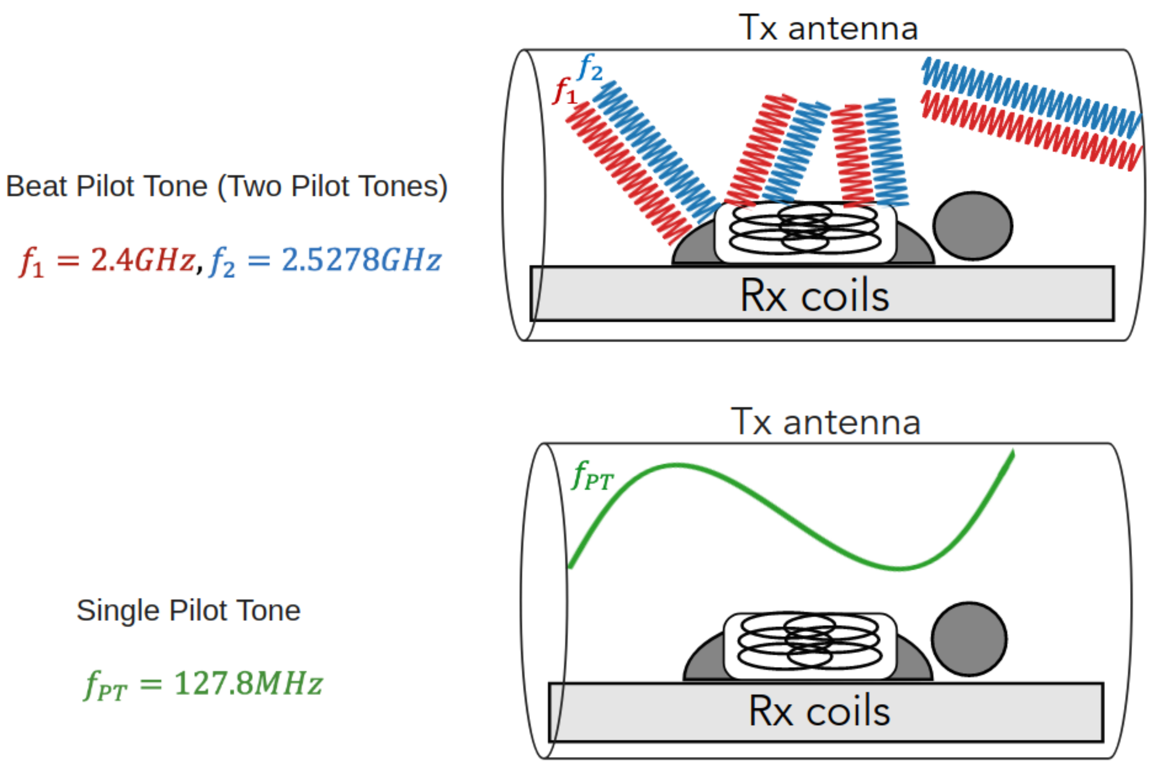

Figure 2: A comparison of PT with BPT, reproduced from [2] by permission from Suma Anand. In both cases, an external RF transmission is applied; however, BPT uses two shorter wavelength signals to achieve higher sensitivity.

3 Methods

3.1 Hardware Details

All experiments were performed on a GE 3T MR750W System. Beat Pilot Tone signals for the final system were generated using a Windfreak SynthHD Dual Channel RF Signal Generator. Since two tones are needed to generate the BPT, the SynthHD is ideal in allowing us to produce both tones with a single device and minimizing hardware complexity of the system. Additionally, it is capable of generating signals between 10MHz and 15GHz, providing additional flexibility in what tones we can use to generate the BPT. It is directly controllable over a command line interface (CLI) and allows control of the frequencies broadcast to a resolution of 0.1Hz and allows a transmission power of up to 20 dBm, suitable for the BPT.

3.2 System Design

When designing a system for clinical use of the Beat Pilot Tone, it is desirable that minimal human intervention is needed between scans to set parameters of the BPT or toggle it off and on. (I will be referring to individual pulse sequences as ”scans” and the entire time a patient spends in the bore as an ”exam”, as this is the internal terminology the GE scanner uses). Adjusting the BPT mid-exam would require additional time and user knowledge of the SynthHD CLI, and the goal of this automated system is to improve the user-friendliness of the BPT. In this design, the operator only needs to start the Beat Pilot Tone software once and can run any number of scans while the BPT frequencies and power are set automatically.

The automated system outlined in this thesis was designed as a python script which can be run on an external computer networked with the scanner and a RF tone generator via TCP. This script controls what RF tones to broadcast based on control variables set by each scan type and prescan values which are experimentally determined parameters such as the center frequency of the imaging bandwidth.

GE's External Scanner Interface (ExSI) is a crucial part of this system on any GE scanners, as it is a convenient way for external hardware to check and adjust parameters on the machine. In order to perform on-the-fly adjustment of the BPT, the automated control system needs to be able to perform four core functions:

1. Listen for system dialog on the scanner to initiate BPT when an appropriate scan begins using a flag set in the sequence name. Whenever an operator starts a scan, ExSI alerts the client when the scanner is prepped, and again when it begins a scan. When the scan is prepped, our system queries the name of the most recent scan and determines whether to begin setting the BPT.

2. Check scanner control variables and prescan values to calculate an appropriate BPT signal for transmission.

3. Communicate with external RF hardware to transmit the BPT signal. We use pySerial to communicate with the SynthHD over a serial port using the CLI.

4. Correctly end the transmission when the current pulse sequence is complete. When ExSI sends an alert that the scanner is idle, we can turn off the BPT using the same CLI.

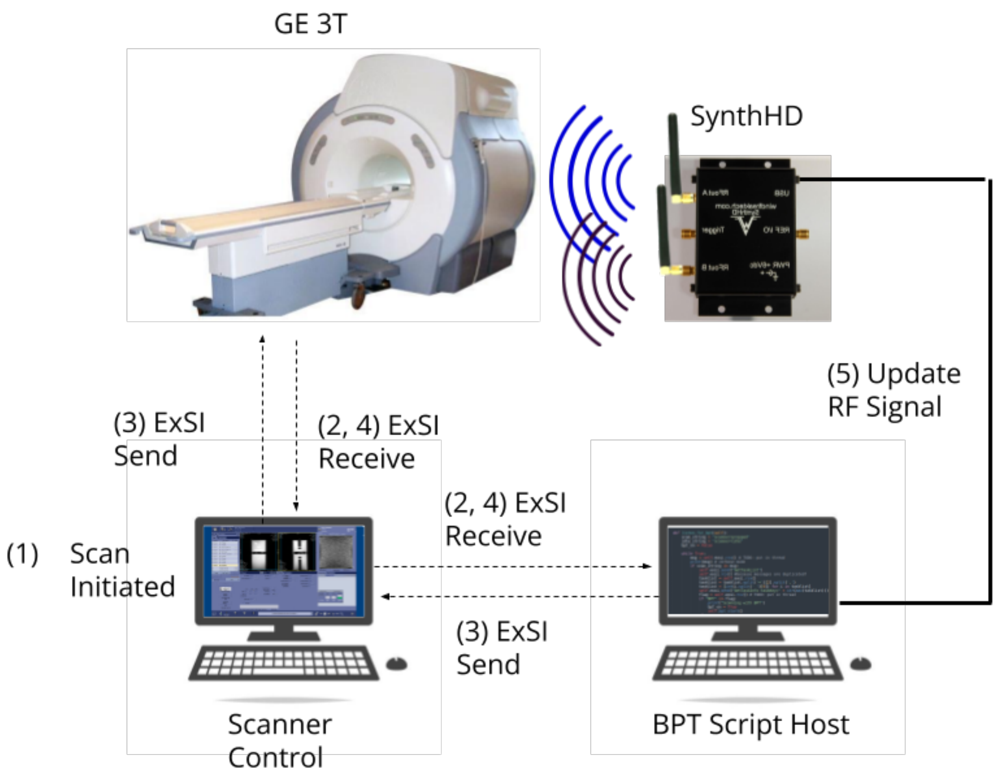

Figure 3: System design of the overall control system with step by step explanation of signal pathway. 1) An operator initiates a scan. 2) In response to the start of a scan, NotifyEvent sends a series of notifications over TCP to the ExSI client on an external computer. 3) The python listener on the external computer sends queries formatted as ExSI commands to get relevant control variables and prescan values. 4) ExSI returns the requested values and the python script calculates the correct frequencies and gain. 5) The external computer transmits the information to the SynthHD over a serial port using the signal generator's built-in command line interface, and the SynthHD begins broadcasting the Beat Pilot Tone.

3.3 ExSI Interface

ExSI, or the External Scanner Interface, is a system for interfacing with a GE MRI system from an external client. ExSI operates as a server within the GE software on the MRI machine, enabling communication with an external computer over a TCP port.

ExSI provides a method to listen for system dialog from the scanner using the NotifyEvent functionality. The proposed automated system uses these events to determine when a scan is about to begin, and queries the current gain, bandwidth, and center frequency. ExSI runs a server which establishes communication with the external computer over TCP, allowing us to send and receive ExSI commands from the same computer that controls the SynthHD.

Table 1: Relevant ExSI commands and their usage in this system.

Command	**Example Usage**	**Returns**
NotifyEvent [all=on/off]	>NotifyEvent all=on NotifyEvent=ok all=on ... <NotifyEvent exam=started <NotifyEvent tps=ready	Causes the scanner to output notifications to ExSI whenever any system events occur. Examples are when the scanner changes state between idle/prescanning/prepped/scanning or when a reconstruction is ready.
GetTaskList	>GetTaskList GetTaskList=ok taskKey=1,2,5,3,4	Returns the list of tasks (scans) in this exam, listed in the order they were created.
GetTaskInfo taskKey=key	>GetTaskInfo taskKey=5 GetTaskInfo=ok taskKey=5 Fiesta BPT	Returns name of the specified scan and state, if any.
GetCVs cvname	>GetCVs oprbw GetCVs=ok taskKey=5 oprbw=83.33	Returns the taskKey of the currently active task and the value of the given control variable. In this case, oprbw is the receive bandwidth in kHz.
GetPrescanValues	>GetPrescanValues GetPrescanValues=ok stat=ok r1=8 r2=29 tg=162 cf=127697962	Returns the most recent prescan values, experimentally determined parameters of the scanner magnetic field and receive setup.

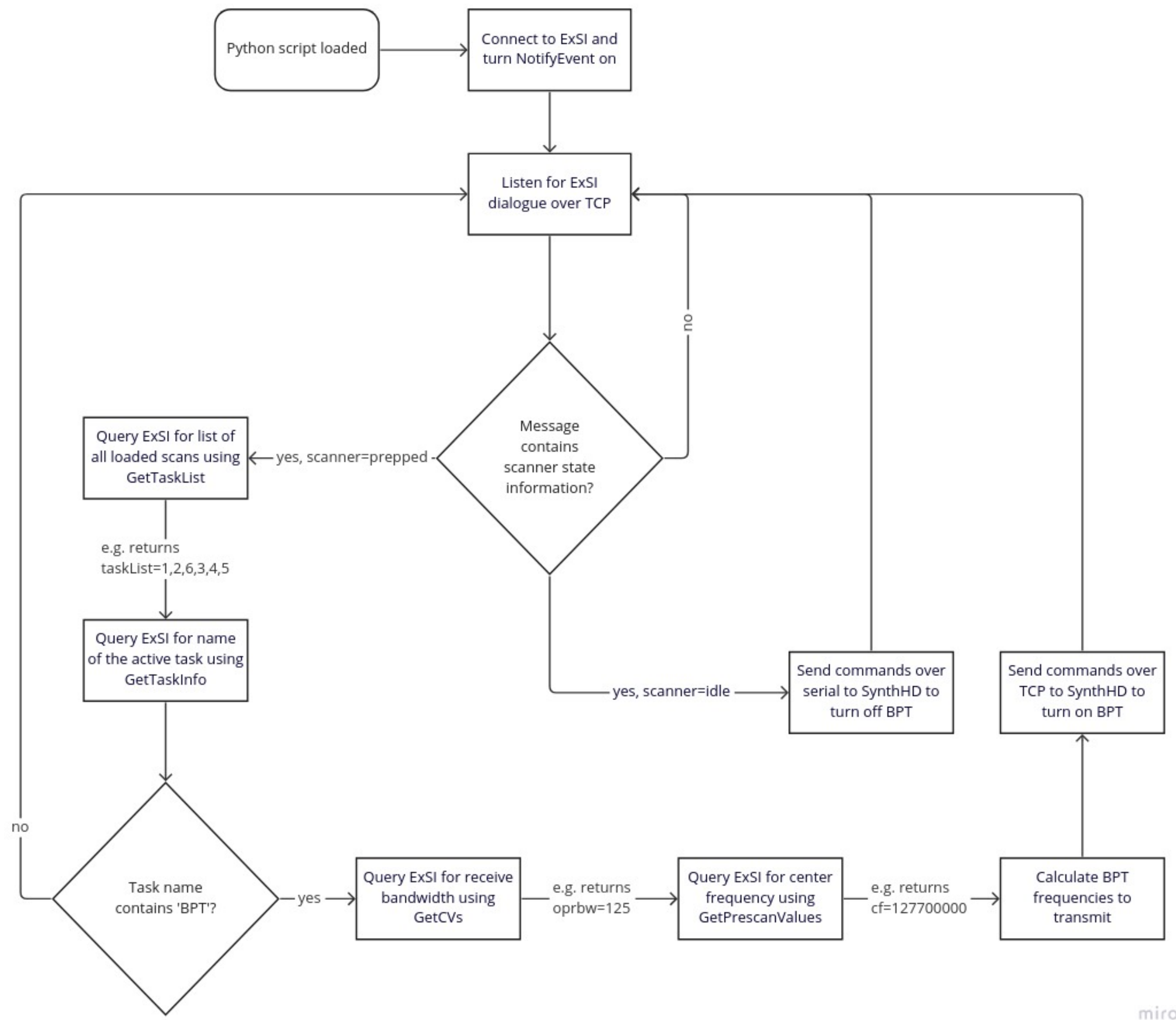

Figure 4: Flow graph showing the control flow of the python client during operation.

3.4 Beat Pilot Tone Signal Generation

The most important characteristic for a pilot tone signal is that it needs to fall within the imaging bandwidth; otherwise, it will not be digitized by the receiver. Thus, the frequency must be relatively close to the Larmor frequency of the imaging plane, but not so close that it interferes with physiological signal in the image. In general, a pilot tone signal can be written in the following form in order to choose parameters that meet these criteria:

$$PT(t) = A \cdot cos\Big(2\pi t\big(\gamma B_0 + (1-\alpha)\, f_{BW}\big)\Big)$$

or alternatively,

$$PT(f) = \frac{A}{2}\delta\big(\gamma B_0 + (1-\alpha)\, f_{BW}\big)$$

Where A is the signal amplitude, γB_0 is the Larmor frequency for a given B_0 field strength, α is the distance from the edge of the field of view as a fraction of the total FOV, and f_{BW} is the bandwidth of the image in k-space. When digitized, the BPT shows up as a line at pixel $\lfloor 0.5(1+\alpha)n_{ro}\rceil$, where n_{ro} is the number of pixels in the readout dimension.

In Beat Pilot Tone, the two broadcasted frequencies must beat at the frequency of the pilot tone while occurring near a higher frequency F which we choose to maximize sensitivity to motion. Thus, we must transmit:

$$BPT_1(f) = \frac{A}{2}\delta(F - \frac{F_{PT}}{2})$$

$$BPT_2(f) = \frac{A}{2}\delta\big(F + \frac{F_{PT}}{2}\big)$$

Where $F_{PT} = \gamma B_0 + (1-\alpha)\, f_{BW}$.

These signals are generated by a Windfreak SynthHD signal generator attached via serial port to a computer in the equipment room of the GE scanner. Both tones are then transmitted via SMA cable into the scan room where they are broadcast by an antenna placed inside the bore of the scanner. This external computer is additionally networked to the host computer in the control room that runs the GUI for the scanner and sets pulse sequences (denominated sdc in the local network).

3.5 Rocker

In order to perform testing of the system on a phantom (a tissue stand-in for scans without a live human subject) with simulated motion, we use a service tool on the GE system called Rocker. This tool is capable of moving the scan bed in small periodic motions to approximate bulk motion of a patient during a scan. For these experiments, we used a sinusoidal motion with a maximum amplitude of 80 mm and a maximum velocity of 20 mm/s. These values were chosen to ensure Rocker completes at least one full cycle during the both types of scans chosen and motion would be as strong as possible.

3.6 Experiments

In order to validate results, tests were performed on two types of common pulse sequences: FIESTA [12] and SPGR [13]. The inclusion of different pulse sequences is to demonstrate the sequence independence of the BPT. For each sequence type, three scans were performed: one with Rocker and BPT active, one with just BPT, and one with neither. The first scan shows the sensitivity of the BPT in detecting motion; the second is a control as there will theoretically be no motion present; and the third tests the ability of the automated control system to correctly turn off the BPT in order to avoid transmitting during a scan where BPT is undesired. These sequences were performed on GE imaging phantoms. BPT is controlled by a flag set in the scan protocol for each pulse sequence; no human intervention is performed on the BPT hardware during the exam to ensure that the control system correctly toggles and sets the BPT.

4 Results and Discussion

4.1 Phantom Scans

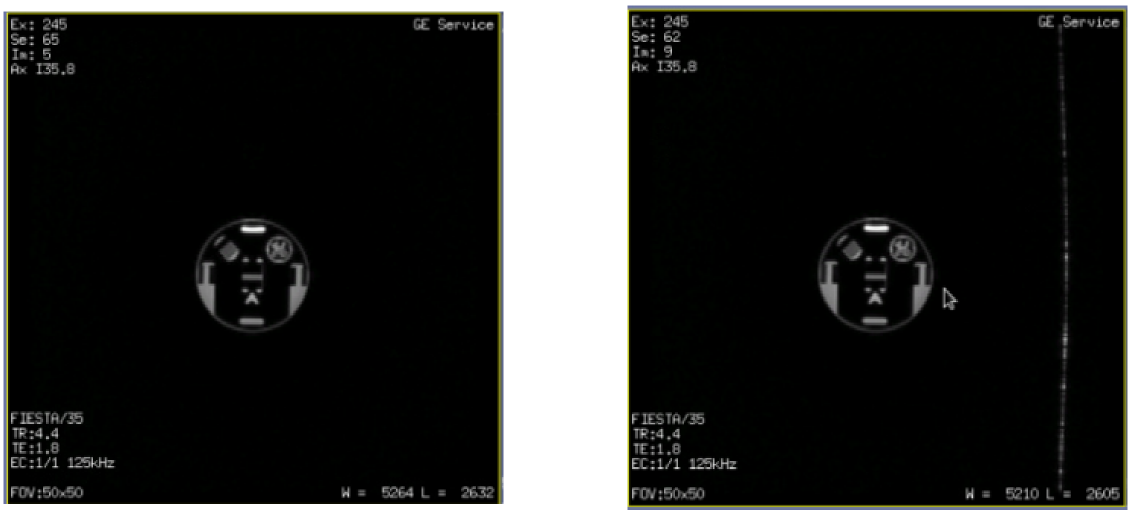

Figure 5: Demonstration of the appearance of a BPT signal in the received image. (left): FIESTA image acquired with a 4.4ms TR. TR is a parameter that determines the time between acquisitions and directly correlates with the time required to fully sample k-space. (right): Same image acquired as FIESTA BPT, showing the streak along the edge of the image bandwidth created by the BPT signal. Note that by appropriately selecting the BPT frequencies, we can acquire a BPT signal which does not interfere with the physiological or phantom signal in the scan.

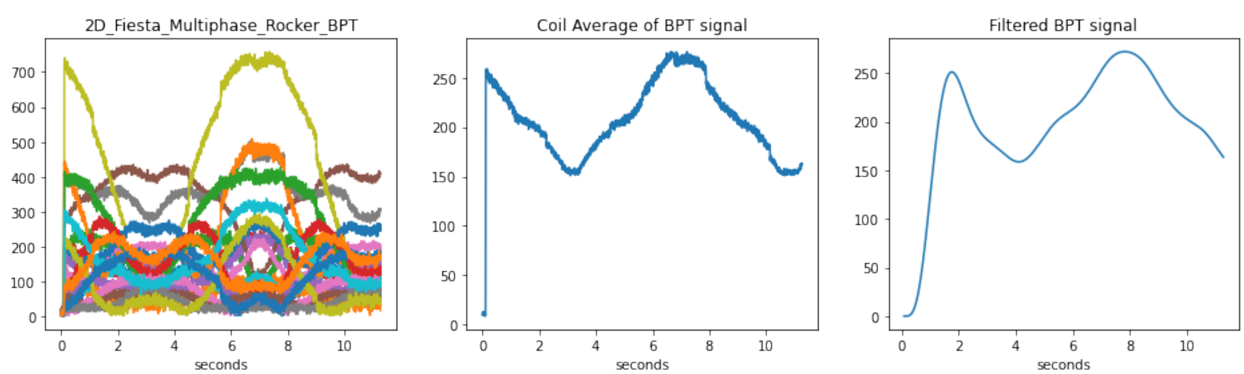

Figure 6: BPT extracted from a FIESTA image with Rocker active showing a clear ability to detect motion.

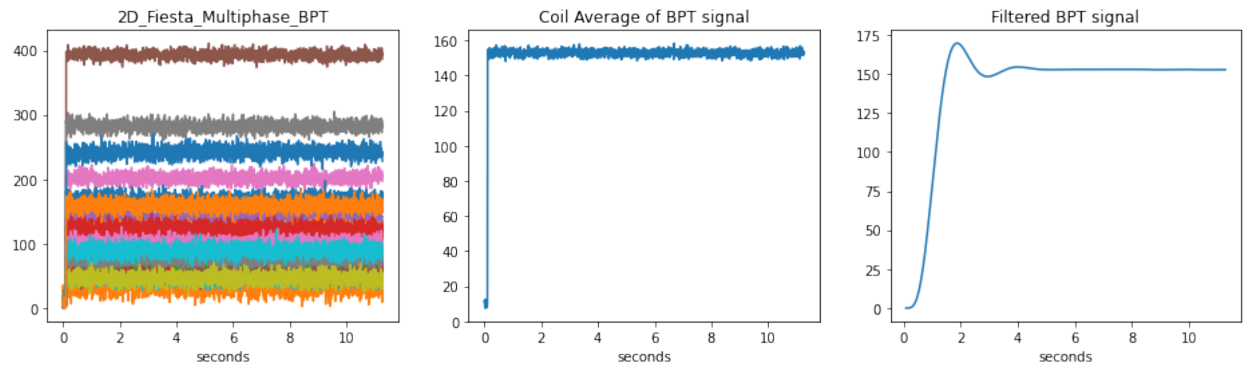

Figure 7: BPT extracted from a FIESTA image with Rocker inactive showing that the BPT strength remains constant in all coils.

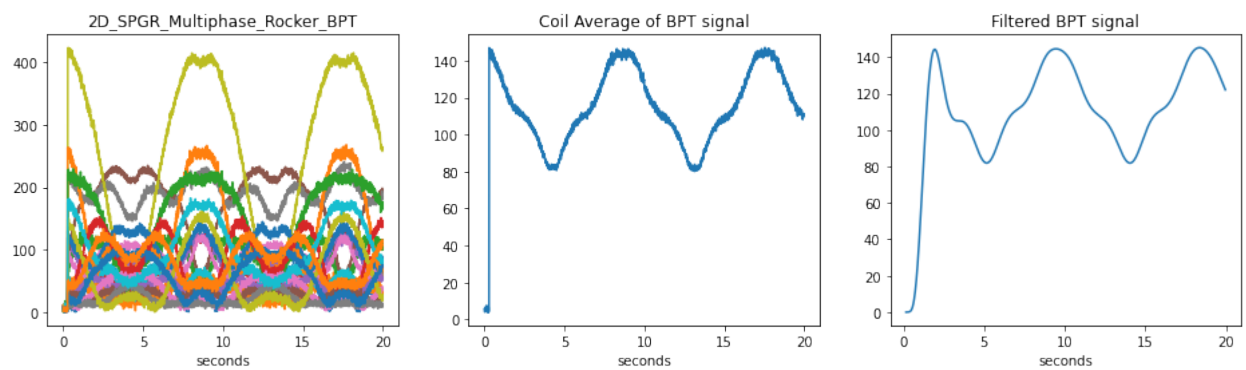

Figure 8: BPT extracted from an SPGR image with Rocker active showing a clear ability to detect motion.

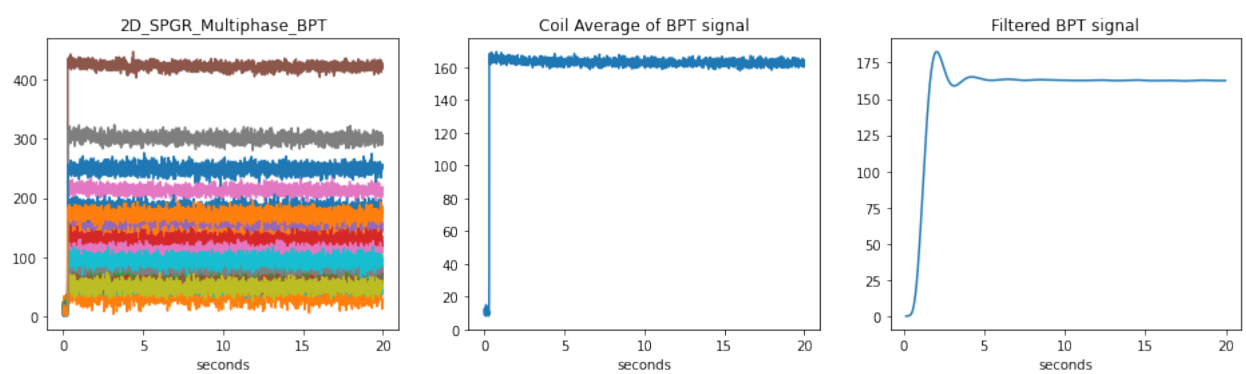

Figure 9: BPT extracted from an SPGR image with Rocker inactive showing that the BPT strength remains constant in all coils. Note that the BPT maintains a similar shape, strength, and periodicity independent of pulse sequence type.

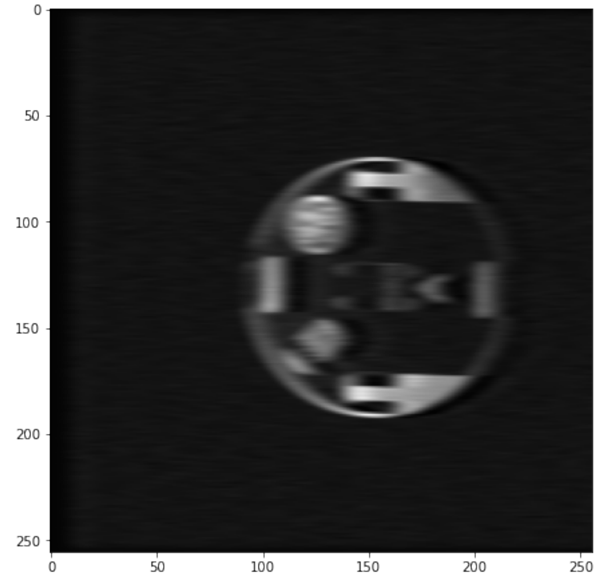

Figure 10: Here are shown the raw images from SPGR (left) and FIESTA (right) with the BPT inactive.

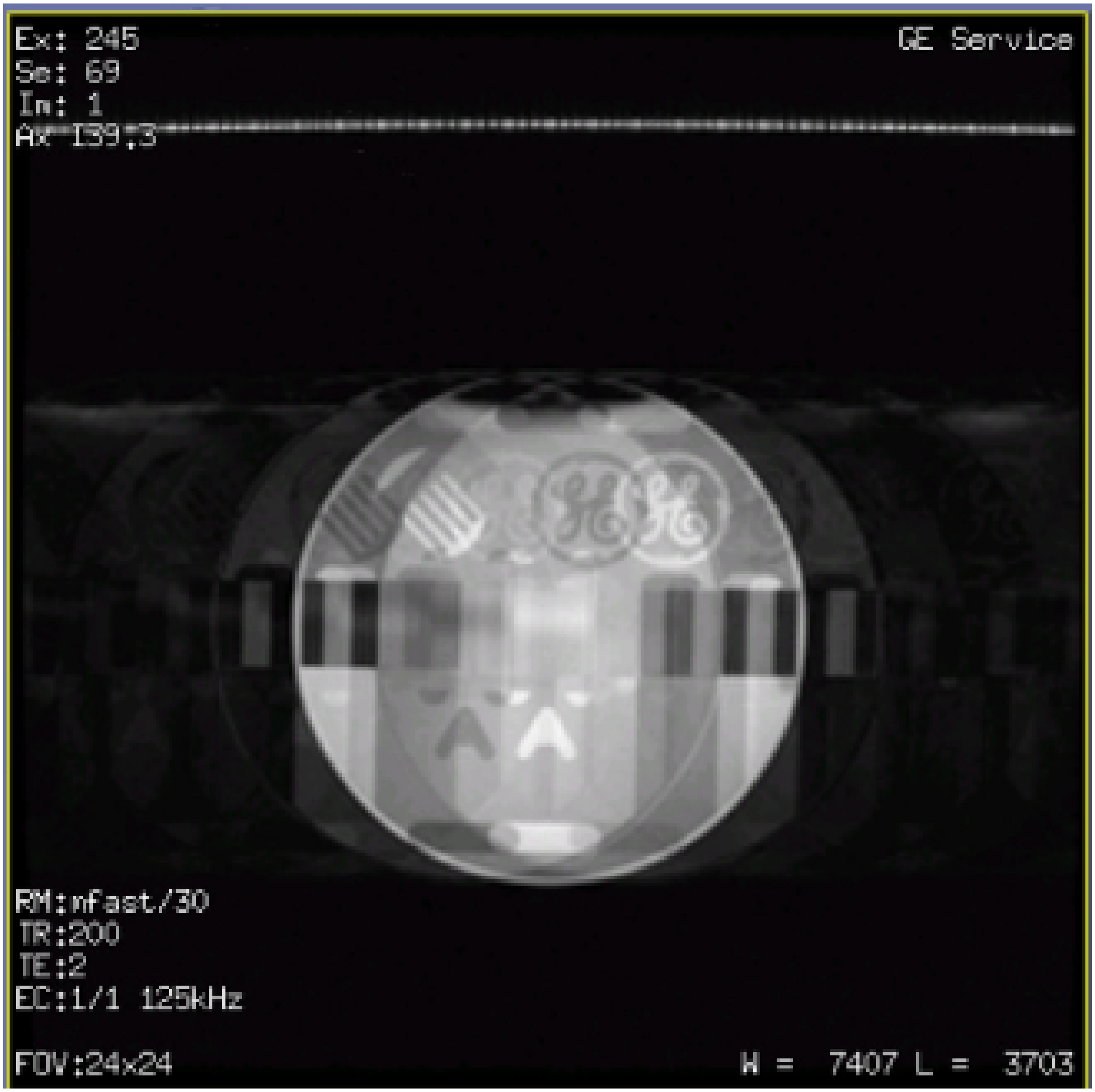

Figure 11: Example reconstruction of a FIESTA image acquired with an extremely large TR (200 ms) showing severe motion artifacts. In this case, the exaggerated TR is used to show the "worst case scenario" for slow pulse sequences and highlight the artifact BPT can be useful in correcting.

4.2 Evaluation

Overall, this thesis replicates the results of [2] showing that Beat Pilot Tone can accurately detect motion in MRI. Additionally, we have demonstrated that this automated control system is able to consistently toggle and set parameters for the Beat Pilot Tone transmission by interfacing with ExSI. The reduction in setup time and the improved ease of use of this automated system will expedite future experiments in Beat Pilot Tone and help pave the way for clinical applications.

4.3 Future Work

One potential avenue for future work on the Beat Pilot Tone is in the transmission of multiple beat frequencies in the same scan. Each receive coil detects the Beat Pilot Tone with varying sensitivity depending on its orientation with respect to the antenna, [2] [1] and using multiple antennas would allow for better measurement of motion in 3 dimensions.

Another potential avenue for future work is combining the Beat Pilot Tone with incoherent sampling techniques for motion deblurring. For example, DISORDER is a technique which uses random sampling of volumetric MRI to minimize artifacts from bulk motion. [14] BPT could be combined with the DISORDER acquisition sequence to further reduce motion artifacts.

5 Conclusion

In conclusion, we have developed an automated control system for practical use of Beat Pilot Tone in a clinical MRI setting. We have demonstrated the effectiveness of Beat Pilot Tone on multiple types of scans, and shown that the system is able to correctly apply the BPT in a complicated MRI exam setting with multiple pulse sequences. Reconstructions validate that the BPT is able to reduce motion artifacts caused by both periodic and aperiodic motion. This makes the Beat Pilot Tone an increasingly practical method for motion correction in a clinical setting.

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