Heart rate measurement of nesting birds using a microphone in a plastic egg

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ABSTRACT

The responses of birds to overflying remotely piloted aircraft (or drones) are poorly understood. While direct observations of behaviour can provide an understanding of wildlife response, this approach is unable to quantify the potential physiological responses of individuals. To do this, a dummy bird egg containing a microphone was substituted into the nests of incubating adult seabirds. Audio recordings were made to capture the sounds of the birds' heart-beat. The recordings were used to calculate a resting heart rate, which was to be compared with the heart rate when a remotely piloted aircraft flew overhead. The focus of this paper is the signal processing methods that were evaluated to process the audio signals to extract the instantaneous heart rate of the animal.

1 INTRODUCTION

The use of remotely piloted aircraft has become common for commercial and recreational activities. For environmental applications, remotely piloted aircraft are particularly useful for making ecological observations as they can produce systematic data of high spatial and temporal resolution (Linchant *et al.* 2015). They are especially useful for population monitoring of animals that can be easily observed from above such as seabirds (Hodgson *et al.* 2016; Hodgson *et al.* 2018). However, when using remotely piloted aircraft in these locations, there is a concern that their use has the potential to disrupt the nesting behaviour of birds.

In aviation activities, Fly Neighbourly airspaces are defined for noise sensitive regions to reduce aircraft noise from disrupting birds in the Great Barrier Marine Park in Queensland, World Heritage Area in Tasmania, Freycinet Peninsula in Tasmania, Port Campbell National Park in Victoria, Phillip Island Nature Park in Victoria, Waitpinga Cliffs in South Australia, Innes National Park in South Australia, Kangaroo Island in South Australia and Symbio Wildlife Park in New South Wales (Airservices Australia, 2018). Within these Fly Neighbourly airspaces, it is recommended that pilots of aircraft fly above nominated altitudes and not change engine speed to prevent disturbing animals. For example, some recommendations are to fly at least 2000 ft above ground level in these regions. However, remotely piloted aircraft are typically flown at less than 400 ft above ground level, which is much closer to the ground and nesting birds, than inhabited aircraft. Hence, investigations of whether the operation of remotely piloted aircraft has the potential to disrupt nesting seabirds are important to ensure their breeding activities are not adversely affected (Hodgson and Koh, 2016).

A study was conducted involving nesting Little Penguins (Eudyptula minor), as shown in Figure 1, to determine whether they are disrupted by remotely piloted aircraft flying overhead. One physiological parameter that was investigated was whether the birds' heart rate increased as a remotely piloted vehicle flew overhead. To do this, a plastic decoy egg, fitted with a wired microphone, was substituted into bird nests of interest. When the bird was incubating the decoy egg, the microphone readily detected the audio from blood pulsations. Audio was recorded using a digital audio recorder which was connected to the microphone by wire.

Decoy eggs fitted with microphones have been used to successfully record blood pulsations in a variety of bird species. This technique has been used on Adelie (*Pygoscelis adeliae*)(Giese, Handsworth & Stephenson 1999; Borneman, Rose & Simons 2014), Yellow-eyed (*Megadyptes antipodes*)(Ellenberg, Mattern & Seddon 2013), Snares (*Eudyptes robustus*) (Ellenberg *et al.* 2011), African (*Spheniscus demersus*) (Nimon, Schroter & Oxenham 1996) and Gentoo (*P. papua*)(Nimon, Schroter & Oxenham 1996) Penguins as well as terns, gulls and oystercatchers (Arnold *et al.* 2011; Borneman, Rose & Simons 2014). While both the equipment used and the method used to infer heart rate has varied, a robust and efficient post-processing technique has not been achieved. In other studies, the heart rate of birds has been calculated using non-auditory methods. For example, researchers have implanted electrodes beneath the skin surface (Diehl and Helb, 1986; Ryden, 1980;Tomlinson, 1991) as well as used Polar heart rate watches (Viblanc et al. 2012) to monitor the electrical activity of the heart. However, these methods are intrusive, they present a variety of animal ethics concerns, and the extent to which experimental apparatus have altered behaviour is unclear. However the audio monitoring method used here is less intrusive but it generates considerable audio data that requires manual or semi-automated post-processing to infer heart rate.

This paper describes signal processing methods that were investigated to determine the instantaneous heart rate of birds from audio recordings, and does not discuss the outcomes of the ongoing experiments involving the flight of remotely piloted aircraft over nesting birds.

Figure 1: One of the nesting penguins that were involved in the study.

2 AUDIO RECORDINGS

Audio was recorded using a wired (Shure) microphone installed inside a plastic, hollow egg, which was connected to a digital audio recorder (ZOOM H2n). A separate video camera was used to record the activity of the bird visually. The audio and video recordings would typically occur over 15 minute periods. The goal of the work presented in this paper was to develop a signal processing method for the audio recordings to enable determination of the instantaneous heart rate of the bird over the measurement period. Previously, researchers listened to audio recordings and manually counted heart pulses in order to determine average pulse rates, which is time-consuming. A typical audio recording, shown in Figure 2(a), contains large amplitude spikes where the bird was moving, causing the microphone signal to overload. Figure 2(b) shows the same audio signal for a single heart pulse, where the waveform is similar to the vibration response of defective bearings with line spalls (Moazen-Ahmadi, Howard, and Petersen, 2015), where researchers attempted to determine the size of a spall defect by measuring the period between successive low-frequency pulses embedded in a complex waveform. The signal processing task here to determine the heart rate is similar, where the duration between two repeating pulse groups are sought, only significantly more complicated by irregular periods, amplitudes, and extraneous noise.

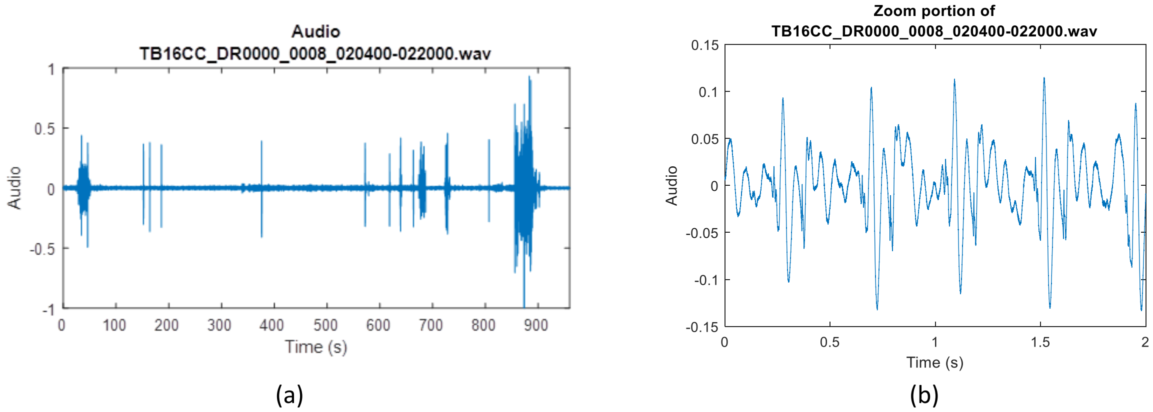


Figure 2 Typical audio recording from the microphone inside a plastic egg (a) over 15 minutes; (b) 2 s.

Figure 3 shows a 5-second audio signal of heart pulses measured using a microphone placed inside a plastic egg while a penguin was sitting on it. The signal was band-pass filtered between 50-200 Hz, and a Hilbert transform was used to determine the envelope signal. There are two main heart sounds in each cardiac cycle of a human heart, known as the first (S1) and the second sounds (S2) (Chen et al., 1995), and these signal features also occur in the recordings of the penguins. The time between two successive S1 sounds is used to determine the instantaneous heart rate, shown in Figure 3 by manual measurements, and varied between 140 to 154 beats-per-minute, which is irregular, and illustrates the large variability of the heart-rate over successive beats.

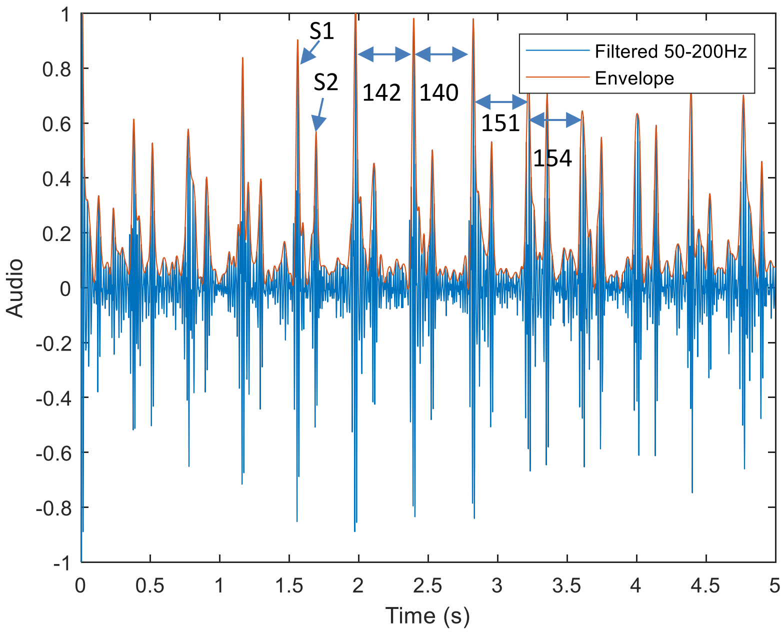


Figure 3: Band-pass filtered and envelope of the audio signal, showing S1 and S2 heart pulse sounds, and the beats-per-minute between S1 pulses.

The following section describes some of the signal processing techniques that previous researchers have used to determine heart rate from non-electrocardiogram (ECG) sources.

3 SIGNAL PROCESSING METHODS

Although there are many papers discussing signal processing methods of ECG signals to determine heart rate, the focus here is on methods to process audio signals. The analysis of heart sounds is called phonocardiography (PCG), where a microphone is usually placed on a patient's chest, and is used to record the sounds that are analysed by a physician. Each heart pumping cycle comprises two major sounds called S1 and followed shortly afterwards by S2, as shown in Figure 3. Other sounds can indicate heart disease or abnormalities. Most researchers have conducted measurements on cooperative human subjects in a laboratory setting, using fixed microphones, special recording equipment, in low-noise environments, which is not the case in this work, and resulted in non-ideal measurements, making determination of the instantaneous heart-rate challenging.

3.1 Previous Methods

Methods that have been used to analyse heart sounds include time-frequency analysis (Chen et al., 1997), Fourier and wavelet analysis (Rajan et al., 1998; Lee and Lee, 1999; Obaidat and Matalgah, 1992; Liang et al., 1997b), energy methods (Haghighi-Mood and Torry, 1995; Liang et al., 1997), neural networks (Hebden and Torry, 1996; Oskiper and Watrous, 2002), Hidden Markov models (Ricke et al., 2005; Schmidt et al., 2010), Synchro-squeezing Transform (Wu et al., 2016).

Zhang et al. (2010) used a peak detection method, combined with fuzzy logic to remove spurious peaks, and thresholds levels, to obtain average heart rates over three pulses.

Chen et al. (2015) used a microphone sensor placed on a human's neck and continuous wavelet transform filter banks to extract peak frequencies for potential candidates of S1 and S2 sounds, then used a threshold method to determine the period between beats.

Martin and Voix (2018) band-pass filtered audio signals from heart sounds, then used a Hilbert transform to extract the envelope of the signal, then used a peak detection algorithm based on thresholds. They avoided spurious pulses by examining the previous estimate of the heart rate and incrementing the analysis window, which assumes that the heart rate is stable over a couple of seconds. As shown in Figure 3, the penguin had a significant variation in heart rate between successive beats, so their method is not suitable for the analysis of the heart rate of birds. Instead, a variation of their method was employed in this study and is discussed later.

3.2 Analyses

The work conducted here involved examining several algorithms to extract the instantaneous heart rate. As mentioned previously, many of the algorithms that have been used by previous researchers involved "high-quality" audio data, with compliant patients, in controlled laboratory environments. Several algorithms were evaluated on audio recordings obtained from field recordings in order to determine what would be most suitable in terms of: providing a good time and frequency resolution of the heart rate; ease of processing for researchers without extensive signal-processing expertise; low computational resources. The Matlab source code and audio files described in this paper have been made publicly available (Howard, 2018).

3.2.1 Short-Time Fourier Transform

Perhaps the simplest method involves band-pass filtering the audio from 50 Hz to 100 Hz, which helps remove background noise. Inspecting the power spectral density of the signal shows peaks between 2.5 Hz (150 bpm) and 3.0 Hz (180 bpm), which is the normal heart rate for the species of penguin in this study. A spectrogram can be plotted, and the peak amplitude in the 2.0 Hz to 3.0 Hz range can be extracted, to show the heart rate versus time, as shown in Figure 4. The block size used for the FFT limits the time and frequency resolution for determining the instantaneous heart rate. Whilst this method is perhaps the simplest to calculate, alternative methods are available that provide better time and frequency resolution.

Similarly, other researchers have used a sliding-FFT window over a 6-second period, to determine the average heart rate, which is suitable for monitoring the heart-rate of humans while exercising. The averaging process hides the heart-rate variability and hence is less useful for the purpose of monitoring the affect an overflying drone has on changes in the heart-rate of a bird.

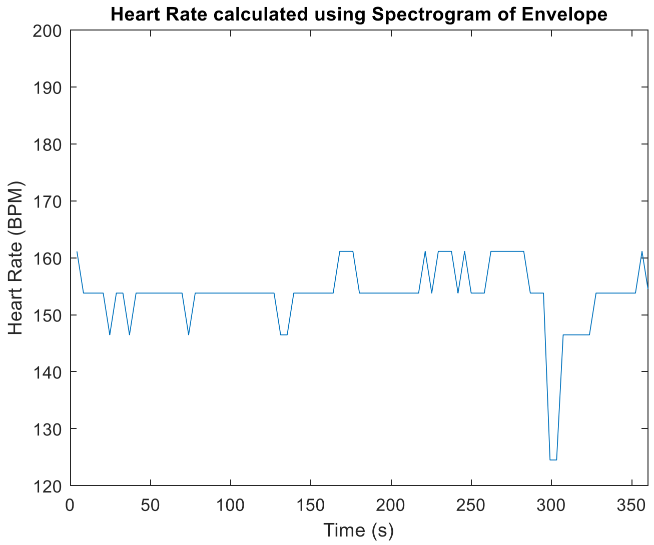


Figure 4: Heart rate of penguin obtained by band-pass filtering 50-100 Hz, Hilbert transform, and performing a short-time FFT.

3.2.2 Sliding Auto-Correlation

Another method involved using a sliding-autocorrelation signal processing method. The audio signal was:

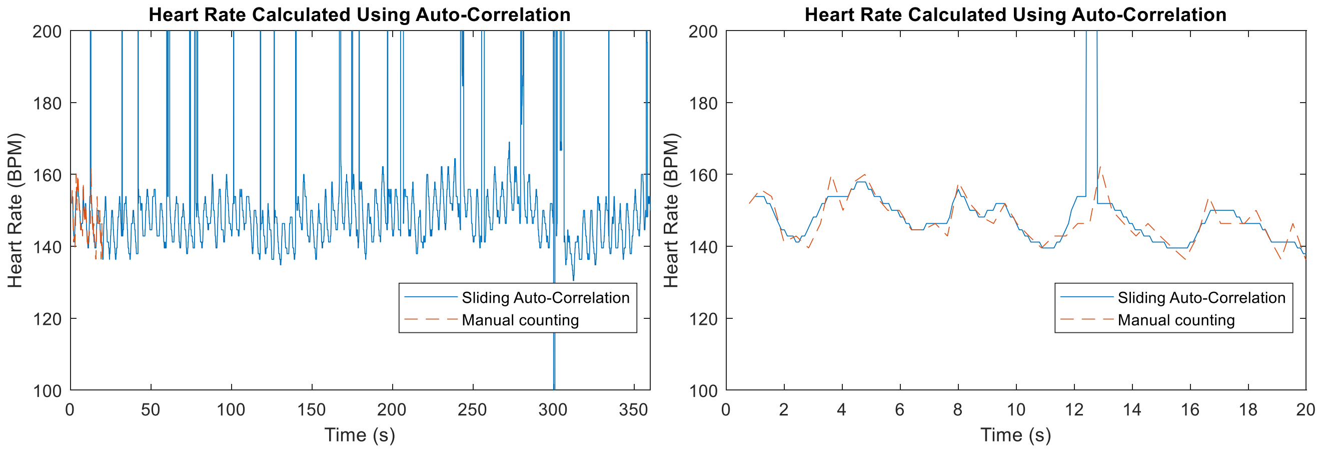
- Band-pass filtered between 50 Hz to 200 Hz.
- Down-sampled (decimated) from 8 kHz to 200 Hz.
- Used a sliding-autocorrelation method, where the sliding window was 2 seconds in length.
- Extracted the “lags” of the auto-correlation that were within the period range of the expected lowest and highest beats-per-minute (100 – 200 BPM).
- Converted the lags into beats-per-minute versus time.

The instantaneous heart rate is shown in Figure 5 for (a) 6 minutes, and (b) for 20 s and also shows the manually estimated heart rate determined by inspecting every S1 pulse for 20 seconds, determining the period, and the instantaneous heart-rate. The results show that the method using the sliding auto-correlation function provides a very good estimate of the instantaneous heart rate. However, in a few regions there were “spikes” in the estimate that are due to the variability in the original audio signal, and should be removed.

3.2.3 Synchro-Squeezed Transform

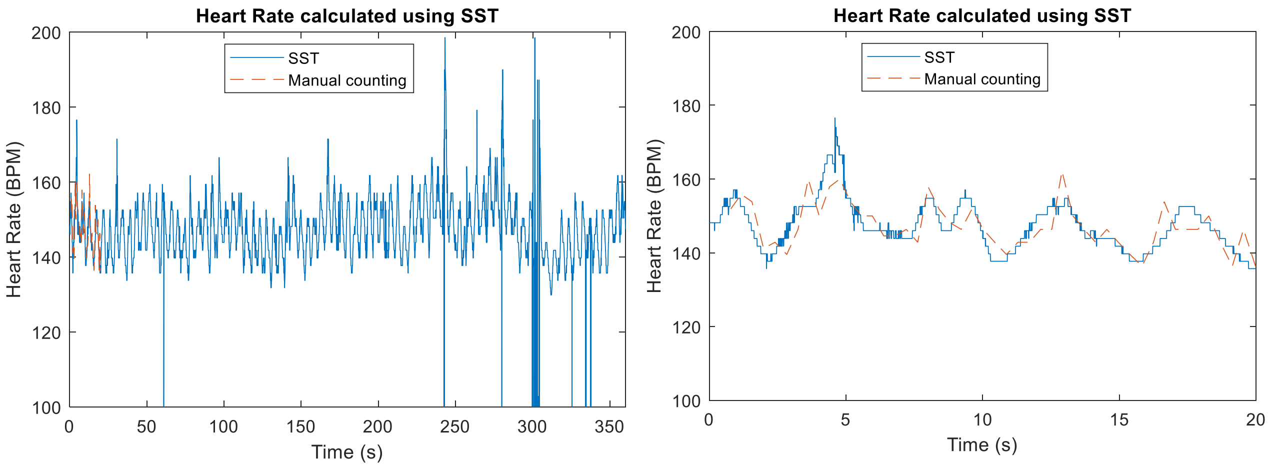
A relatively new signal processing method has been developed called a Synchro-Squeezed transform (SST), which can be used to extract instantaneous heart-rates from pulses (Wu et al., 2016). This method is computationally expensive but provides good time and frequency resolution with little user intervention. Figure 6 shows the instantaneous heart rate calculated using the wavelet SST method over (a) 6 minutes, and (b) over 20 s and compared with the heart-rate determined by manually counting pulses. The processing method involved:

- Band-pass filtering the audio between 50 Hz and 200 Hz.
- Down-sampling (decimating) the audio to 200 Hz.
- Using a Hilbert transform to calculate the envelope of the signal.
- Using a (Amor) wavelet synchro-squeezed transform with 48 voices-per-octave.
- Extracting the highest amplitude within the frequency range corresponding to the lowest and highest expected beats-per-minute.



(a) (b)

Figure 5: Heart rate calculated using a sliding-autocorrelation signal processing method over (a) 6 minutes and (b) over 20 s and compared with manual counting.



(a) (b)

Figure 6: Heart rate calculated using wavelet Synchro-Squeezed (SST) transform over (a) 6 minutes and (b) over 20 s and compared with manual counting.

The SST method is computationally expensive and can take relatively long times (in the order of minutes) when used in Matlab. The decimation of the envelope signal to 200 Hz reduced size of data and therefore the computational requirements, which enabled processing of the 6-minute recording.

3.2.4 Peak Detection of Envelope Signal

A signal processing method was created that involved detecting only the S1 pulses and measuring the period between successive S1 pulses to determine the heart-rate. This method could be described as an automated method of the manual pulse counting method. The signal processing method that used was:

- Band-pass filter the audio signal from 50 Hz to 100 Hz.
- Use a Hilbert transform to calculate the envelope of the squared audio signal (i.e. rectified).
- Use Matlab's findpeaks function to identify peaks in the envelope signal, where successive peaks have a minimum time separation of $(1/\mathrm{BPM}_{\mathrm{high}}) \times 60$, where $\mathrm{BPM}_{\mathrm{high}}$ is the highest expected beats-per-minute, which is 200 BPM for the species of penguin in the study.
- Find the subset of the peaks in the envelope signal that have an amplitude greater than 0.1.

Figure 7 shows the outcome of performing the steps described above with the red circle markers indicating the identified S1 sounds. The next step involved calculating the duration between the successive peaks, which corresponds to the S1 sounds, and determining the instantaneous beats-per-minute, as shown in Figure 8.

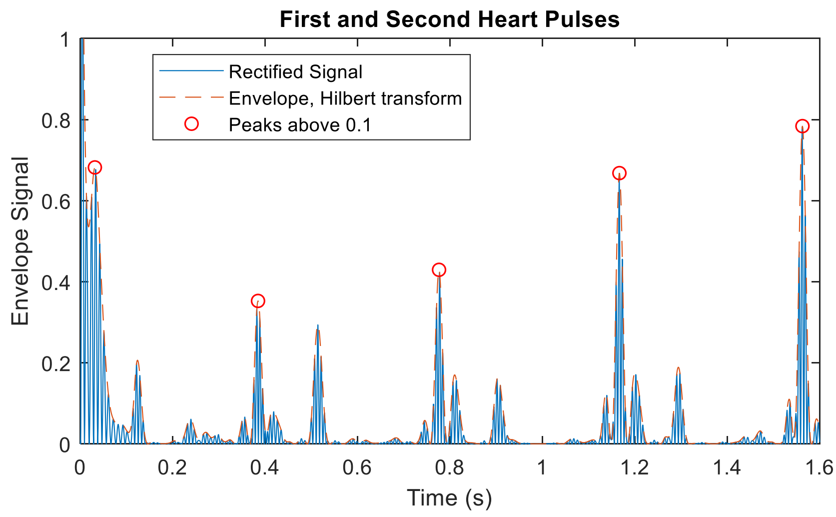


Figure 7: Envelope of the rectified audio signal, showing the peaks that were detected.

Figure 8 shows the instantaneous heart-rate calculated by measuring the time between successive S1 sounds, over (a) 6 minutes, (b) over 20 seconds and compared with manual counting. The results show that there is a very good agreement between the signal processing and the manual counting methods.

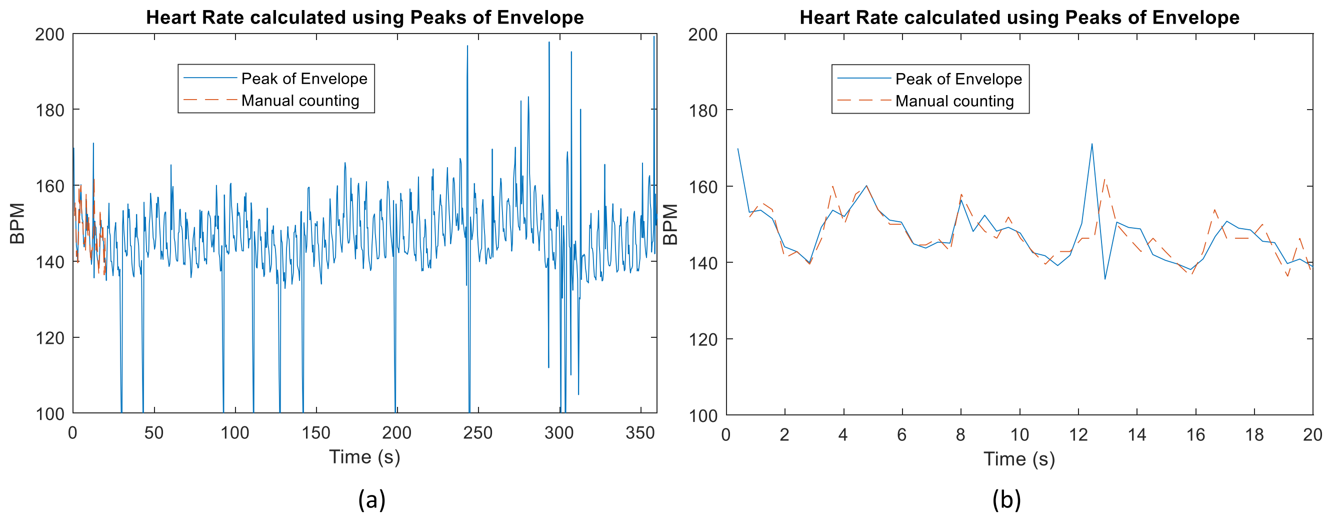


Figure 8: Heart rate calculated using peaks in the envelope signal over (a) 6 minutes and (b) over 20 s and compared with manual counting.

4 CONCLUSIONS

This study involved the evaluation of several signal processing methods to determine the instantaneous heart-rate of a penguin, obtained from audio recordings when a penguin was incubating a plastic decoy egg fitted with a microphone. Although previous researchers have successfully applied signal processing algorithms on audio signals to extract heart-rates, these have been in well-controlled environments, and resulted in high-quality recordings, compared to the field recordings collected in this work. Several algorithms were evaluated to determine their efficacy in terms of time and frequency resolution to extract the instantaneous heart-rate, the amount of manual intervention required in the processing, and the computational resources required. The methods that were evaluated included the short-time Fast Fourier Transform (sFFT), sliding-autocorrelation, wavelet synchrosqueezing (SST), and peak detection of the envelope signal. It was found that the peak detection of the envelope signal provided good time and frequency resolution, which compared very well with manual pulse counting methods, required no intervention, and had low computational requirements compared with the wavelet SST method. The method could be slightly improved by examining the statistics of the envelope signal to automatically determine an appropriate threshold value for the detection of the peaks corresponding to the S1 heartbeat sound.

The work involving the experimental campaign of collecting audio recordings of the heart-beat sounds from nesting birds when a drone overflies is ongoing, and the findings will be published.

STATEMENT OF ETHICS APPROVAL

The audio recordings used in this work were part of a study that has approval from the University of Adelaide's Animal Ethics Committee (S-2016-180).

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