Institution: University of Surrey

Unit of Assessment: 10 (Mathematical Sciences)

Title of case study: Symmetric Projection Attractor Reconstruction (SPAR) Improves the Quality and Relevance of Respiration Monitoring Device Data

Period when the underpinning research was undertaken: 2013-2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Philip Aston	Professor of Mathematics	September 1989 – present

Period when the claimed impact occurred: 2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact (indicative maximum 100 words)

The University of Surrey's work on analysing the data collected by Iceni Labs non-contact respiration monitoring device *SafeScan* has had a direct and significant impact on Iceni Labs' ability to bring their technology to market in a timely manner. It has allowed them to have significant first mover market advantage and they are now confident that their technology is world leading. Our analysis showed that their data had a poor signal-to-noise ratio due to the combination of chest and abdominal movement being detected. Iceni Labs redesigned their hardware so that their device could be repositioned which resulted in much cleaner signals, in which the chest and abdominal motion could be clearly distinguished, which are more suitable for analysis.

2. Underpinning research (indicative maximum 500 words)

The underpinning research consists of a new method for visualising and quantifying "approximately periodic" time series data and is known as **Symmetric Projection Attractor Reconstruction (SPAR).** It was developed in the context of cardiovascular time series (e.g., continuous blood pressure, electrocardiogram (ECG)) but the general methodology is more widely applicable. The impact occurred in the context of respiration data.

The problem that the research addresses is one of recognising changes in the morphology and variability of a waveform which, in a clinical context, can aid with diagnosis of many diseases. This is a challenging problem as physiological time series data are irregular, non-stationary and noisy.

Large volumes of data can be collected over hours or days at high sampling frequency. To see the detail of individual cycles in such data, it is necessary to zoom in to a very small-time interval and even then, detecting differences with the data in another time interval is not easy. Our approach consists of plotting the data in a three-dimensional phase space and then projecting down to a particular plane which provides a simple but effective way of filtering out much of the baseline variation, which is one type of noise that is commonly found in the data (see Fig. 1). In this two-dimensional view of the data, which we refer to as an attractor, a single loop corresponds to one cycle in the data. If the data is exactly periodic, this phase space representation corresponds to a single closed loop but if the data varies significantly from cycle to cycle, then this would result in a more disperse attractor. This makes it easy to quantify variability in the data. The shape of the attractor is determined by the morphology of the signal and this representation makes changes in morphology easy to recognise as well. Since the attractor is in a bounded domain, changes in morphology and variability are easy to detect visually and algorithmically.

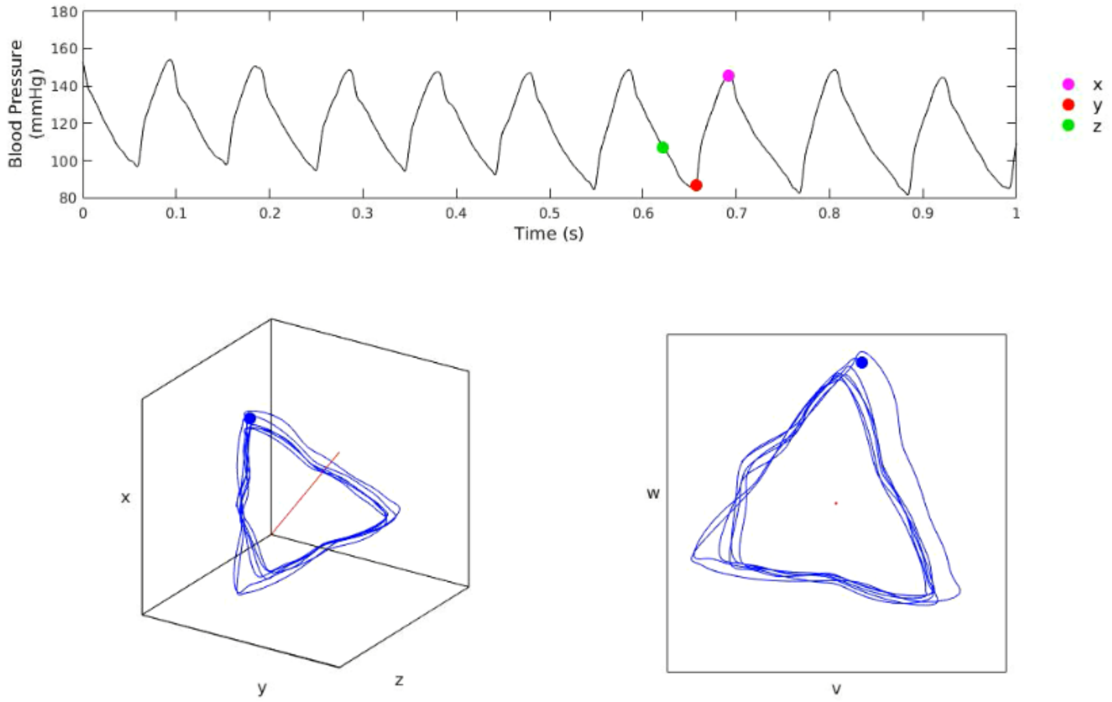

Figure 1: Three points track through a signal (top) are plotted in three-dimensional phase space (bottom left). When viewed in the direction of the red line, a two-dimensional attractor is obtained (bottom right).

The attractor is generated in three-dimensional phase space by using Takens' delay coordinates. We project the attractor onto the plane orthogonal to a particular vector that corresponds to vertical translation of the signal. By considering the frequency response functions of the variables that define the plane, we have showed that the low frequency baseline variation is filtered out in these variables. We prove that our two-dimensional attractor derived from a periodic function has threefold rotational symmetry if the time delay parameter τ is chosen to be one third of the period. For approximately periodic data, we thus choose τ to be one-third of the average cycle length in a window of data and this gives our attractor an approximate threefold rotational symmetry. This means that the attractor does not change shape as the cycle length in the data changes so that changes in the attractor are associated with morphology changes **[R1, R2].**

Heart Rate Variability (HRV) methods consider only beat-to-beat intervals and are a popular way of analysing cardiovascular data. Indeed, a search shows over 38,000 papers that refer to HRV, with over 2,500 papers published in each of the last 4 years. But by considering only the beat-to-beat intervals, all the valuable morphology information in the signal is discarded. That is why we state that "***it is time to move beyond HRV and to develop a new generation of methods of analysis of physiological data that analyse all of the data contained within a particular waveform***" **[R1]** with SPAR being one such method. We have also showed that our SPAR method can detect changes occurring in time series data that are completely missed by HRV **[R3].**

Features can be extracted from the attractor which quantify particular aspects. These can be combined with machine learning to classify the data. One example of this is classification of gender from human ECG signals for which the SPAR features obtained an accuracy of 96% whereas using popular ECG intervals only gave 78% **[R4]**. When classifying mice as either wild type or having a genetic mutation associated with sudden cardiac death from their ECG signals we obtained an accuracy of 87% using only SPAR features, which jumped to 96% when SPAR features were combined with ECG intervals and amplitudes **[R5]**. An alternative is to use the attractor images as input for a deep learning neural network for classification **[R6].**

The paper **[R1]** describing the foundations of the SPAR method was chosen by the journal *Physiological Measurement* as one of their best six papers for the Highlights of 2018 collection. It has been downloaded from the journal website over 3,500 times since publication in March 2018.

3. References to the research (indicative maximum of six references)

[R1] PJ Aston, MI Christie, YH Huang and M Nandi. Beyond HRV: attractor reconstruction using the entire cardiovascular waveform data for novel feature extraction. Phys. Meas. 39, 024001, 2018. DOI: 10.1088/1361-6579/aaa93d

[R2] M Nandi, J Venton, **PJ Aston**. A novel method to quantify arterial pulse waveform morphology: attractor reconstruction for physiologists and clinicians, Phys. Meas. 39, 104008, 2018. DOI: 10.1088/1361-6579/aae46a

[R3] PJ Aston, M Nandi, MI Christie and YH Huang. Comparison of attractor reconstruction and HRV methods for analysing blood pressure data. Comp. Cardiol. 41, 437-440, 2014. ISSN 2325-8861

[R4] JV Lyle, PH Charlton, E Bonet-Luz, G Chaffey, M Christie, M Nandi and **PJ Aston**. Beyond HRV: Analysis of ECG signals using attractor reconstruction. Comp. Cardiol. 44, 091-096, 2017. DOI: 10.22489/CinC.2017.091-096

[R5] E Bonet-Luz, JV Lyle, CL-H Huang, Y Zhang, M Nandi, K Jeevaratnam and **PJ Aston**. Symmetric Projection Attractor Reconstruction analysis of murine electrocardiograms: Retrospective prediction of Scn5a+/- genetic mutation attributable to Brugada syndrome. Heart Rhythm O2 1, 368-375, 2020. DOI: 10.1016/j.hroo.2020.08.007

[R6] PJ Aston, JV Lyle, E Bonet-Luz, CL-H Huang, Y Zhang, K Jeevaratnam and M Nandi. Deep learning applied to attractor images derived from ECG signals for detection of genetic mutation. Comp. Cardiol. 46, 097, 2019. DOI: 10.22489/CinC.2019.097

Key Grants:

- Continuous Information Extraction Using Reconstruction of Attractors from an ECG Signal, EPSRC Impact Acceleration Account, £20,000, August 2014 – February 2015.
- Using Reconstruction of Attractors Method to Extract Diagnostic Information from Engine Sensor Data, EPSRC Impact Acceleration Account, £19,678, March 2015 – August 2015.
- Using Attractor Reconstruction Methods to Classify Mouse ECG Data, EPSRC Impact Acceleration Account, £10,365, January 2017 – March 2017.
- Attractor Reconstruction for Early Detection of Fever and AF, EPSRC Impact Acceleration Account, £30,386, April 2017 – November 2017.
- Detection of the Presence and Progress of Covid-19 from Data, EPSRC Impact Acceleration Account, £7,000, August 2020 – September 2020.

4. Details of the impact (indicative maximum 750 words)

Professor Philip Aston led the evaluation of the respiration data obtained by *SafeScan*, a non-contact respiration monitoring device being developed by Iceni Labs that uses radar technology to assist medical staff in the early identification of worsening patient symptoms requiring medical intervention. By applying the Symmetric Projection Attraction Reconstruction (SPAR) method to the respiration data collected from *SafeScan*, Professor Aston informed the redesign of the *SafeScan* hardware and in doing so enabled Iceni Labs to both access new algorithmic tools and gain a significant market advantage.

Informing the development of a non-contract respiration monitoring medical device, *SafeScan*

Early identification of the need for medical intervention is essential as it results in improved patient outcomes and survival rates, for example, after surgery or in critical care patients. Previous research and development had focused primarily on cardiovascular monitoring. However, respiration rate is one of the most important vital signs for identifying deteriorating health but it is currently under-utilised. One study found that ‘by-eye’ measurements by medical staff were unreliable with 52% of doctors missing abnormal respiratory rates using conventional visual spot assessment methods [Philip et al., J. Clin. Monit. Comput. 29, 455-60, 2015]. Existing devices for measuring respiratory rate are cumbersome, reduce patient mobility and, due to their unreliability, are under-utilised. *SafeScan* is radar-based and so is non-contact, which makes it ideal for medical use. It will give medical and healthcare staff a reliable, real-time indication of respiratory rate which will improve observation accuracy and reduce nursing workload. *SafeScan* is able to identify the need for medical intervention before other existing technologies on the market can do so **[S1]**.

The *SafeScan* device collects multi-channel data at equally spaced distances from the antenna, thus detecting any motion at each distance from the device. It is conventionally placed with the radar normal to the body either from the front or the back. In a hospital setting, it is normally placed underneath the patient’s bed. Professor Aston and his team applied their SPAR method to each relevant channel separately. The data was very noisy but by smoothing it, it was possible to generate an attractor from some channels. However, since each channel of the radar device effectively detects any motion on a spherical shell of a particular radius centred on the radar, it became clear that the signal being detected was being generated not only by chest movement (which is desirable), but also by abdominal movement (which is not desirable). This combination of effects was producing very noisy signals that were hard to analyse and were not clearly detecting the motion of interest in the chest. As a direct result of Aston’s findings, Iceni Labs redesigned the hardware of their system so that the radar can be positioned with a direct line in free space between the radar and the patient. This has meant that the radar can be positioned at the foot of the bed so that the chest motion and the abdominal motion are detected on different channels and so can be clearly differentiated. Dr Dylan Banks (Founder and Knowledge Director, Iceni Labs) reported that this redesign “*allowed for us to significantly improve our signal-to-noise ratio and has opened up a range of new algorithmic processing tools that were otherwise unavailable to us*” **[S2]**. In summary, Aston’s work has resulted in a cleaner and more relevant dataset for distinguishing characteristic change in breathing patterns associated with disease.

Significantly improved market advantage for Iceni Labs

Iceni Labs is a UK-based SME developing science and technologies for use in the medical and human security sectors. Dr Dylan Banks reports that work with Professor Aston on *SafeScan* “*has had a direct and significant impact on our ability to bring our SafeScan radar technology to market in a timely manner. This has allowed for us to have significant first mover market advantage and we are now confident that our technology is a world leader*” **[S2]**. Dr Banks further reports that “*Iceni Labs has recently set up a US subsidiary and in part due to their work that we have taken collaboratively with University of Surrey we have now made the decision to position SafeScan as front and centre of our US development pathway*” **[S2]**.

Thus, Professor Aston’s work has had impact both on the technological development of the *SafeScan* device and on the market opportunities available to Iceni Labs.

5. Sources to corroborate the impact (indicative maximum of 10 references)

[S1] SafeScan Medical https://www.icenilabs.com/medical

[S2] Testimonial Letter from Dr Dylan Banks, Founder and Knowledge Director, Iceni Labs.