ECG COMPRESSION USING PCA WITH POLYNOMIAL ESTIMATION OF HIGHER ORDER COEFFICIENTS

David Hamilton,~~,~~ William~~W~~ Sandham, Alberto Blanco
Dept. of Electronic and Electrical Engineering, University of Strathclyde
204 George Street, Glasgow, G1 1XW, Scotland, UK
Tel.: +44 141 548 2508: Fax. +44 141 552
e-mail: d.hamilton@eee.strath.ac.uk

ABSTRACT

~~-~~*An ECG compression technique which achieves very low bit rates ~~of~~ is ~~12bps is~~ presented. Principal Component Analysis (~~-~~PCA) is used prior to identifying non-linear relationships between the orthonormal eigenvectors. Polynomials are used to approximate higher index transformed coefficients from lower ones. Reconstruction is similar to that used in the Karhune~~u~~n-Loeve transform (KLT) technique but some of the coefficients have been estimated rather than stored explicitly. Exceptionally low bit rates have been achieved with good reconstruction appearance. For very low bit rates, improvements are consistently seen over KLT and ~~however~~ further work is ~~required~~ concentrating on generating ~~for~~ clinically acceptable performance on all examples ~~possibly~~ through relaxing the bit rate requirements slightly to achieve lower reconstruction errors.*

1~~I.~~ INTRODUCTION

Lossy data compression is often appropriate in applications such as video, electrocardiogram and seismic where archival storage and transmission demand reductions in the data volume.~~DATA compression is becoming increasingly important for the archiving and transmission of various data. Lossy compression is sometimes acceptable in certain situations, including electrocardiogram (ECGs), seismic and video data.~~

~~A lossy ECG compression technique, known as~~ The Karhunen-Loeve Transform (KLT) [1], used Principal Component Analysis (PCA) in ~~.~~ a lossy ECG compression technique, which ~~This~~ performed~~s~~ linear decomposition of the data into orthonormal eigenvectors and corresponding coefficients.~~,~~ Reconstruction uses a linearly weighted recombination of the eigenvectors and a *subset* of the PCA coefficients thereby giving compression.

This work~~paper describes a scheme which~~ uses the first linear PCA coefficient but *estimates* higher order coefficients (in place of storing them in full). The estimates are generated ~~through~~ from a polynomial which links them to the first transformed coefficients. ~~The result is normally reasonable reconstruction quality at extremely low data rates.~~

2 ~~II.~~ KARHUNEN-LOEVE TRANSFORM ECG COMPRESSION~~LINEAR PCA COMPRESSION~~

Since the technique uses KLT as a starting point, a brief review of this established technique is presented first. KLT requires fiducial 'trigger' points around each beat to give a set of ***p***-dimensional vectors, ***X***, whose ***j***th member is X_j and whose mean ***M*** is subtracted from each beat to give the set X'. A covariance matrix, ***C***, for this set is derived whose eigenvectors, ***E***, are arranged in magnitude order giving the transformation basis vectors. The transformed coefficients are thus:

$$Y_j = E \, . \, X'_j$$

The reconstructed (or inverse transformed) signal can readily be obtained thus:

$$X_i = E^{-1} . Y_j + M$$

where $E^T = E^{-1}$~~;~~

since the basis vector matrix ***E*** is orthonormal with transpose matrix E^T.

This is effectively a co-ordinate transformation where the original ***p*** dependant variables axes are transformed to ***p*** orthonormal axes in magnitude order, giving scope for compression by storing only the first p' ($< p$) coefficients and eigenvectors.

3 ~~III.~~ METHOD and RESULTS

A standard KLT transform is first performed as described above. KLT requires ~~Normally~~ the first p' transformed coefficients for each beat to be~~are~~ stored in addition to the first ***p'*** eigenvectors common to all beats. ~~. These form a fixed overhead independent of the number of beats of typically 128 bytes for each eigenvector. It was noted that~~ Any non-linear relationship between successive transformed coefficients of the same beat ~~(Fig. 1)~~ can be identified~~existed by~~ by plotting one ~~transformed coefficients on~~ principal component axis ~~1 (PCA1)~~ against another.~~versus principal component axis 2 (PCA2).~~ Note that linear relationships have already been removed by KLT. This scheme operates by calculating a polynomial of best fit to describe this non-linear relationship as shown on Figure 1. Thus for any given beat, an estimate of the coefficient on PCA2, ($y_{i2'}$) may be obtained using the stored coefficient on PCA1, (y_{i1}) obviating the need to store y_{i2} explicitly. The 2-dimensional ~~(2-D)~~ curve, $f_{1.2}(y_{i1})$, required to carry out the estimate is found using a standard analytical method[2] and defined by, say 4 coefficients for the complete set of beats. This represents a minimal additional overhead. A family of curves, $f_{1.k}(y_{i1})$ is found relating y_{i1} to the first few (typically four) transformed coefficients.~~ This is analogous to shifting energy from higher index principal coefficients to the new 'non-linear' principal coefficient as shown for an example of an MIT-BIH signal in~~. Figure 1(b) and Figure 1(c) show the curves used to estimate the second and third coefficients for another record. ~~-~~Figure 2 illustrates how greater emphasis may be placed on the lower coefficients in this way. Although in practice, the associated energy is accessed through the estimates using the curves, Figure 2 illustrates the effect graphically.

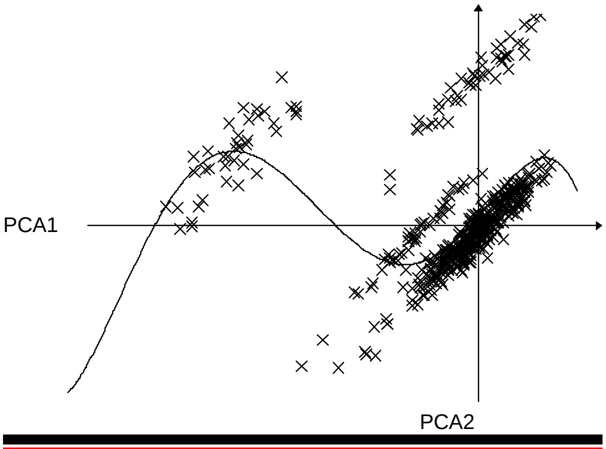


Fig. 1(a)
Fifth order polynomial to capture energy relating PCA2 to PCA1 coefficient for sample MIT-BIH data set of 1000 beats.

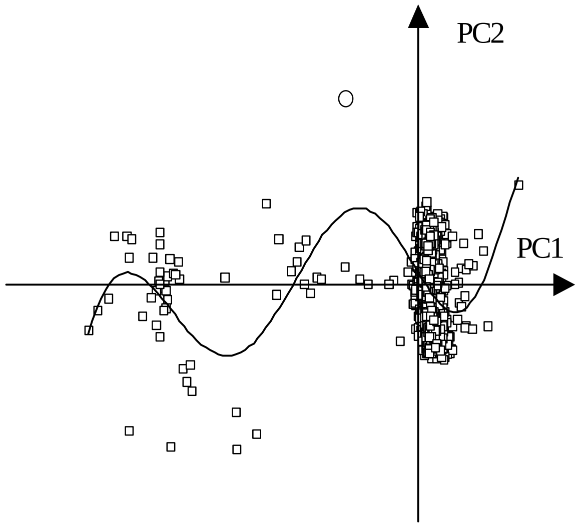


Fig. 1(b)
Second principal coefficeint versus first principal coeffecicent for MIT-BIH record 205

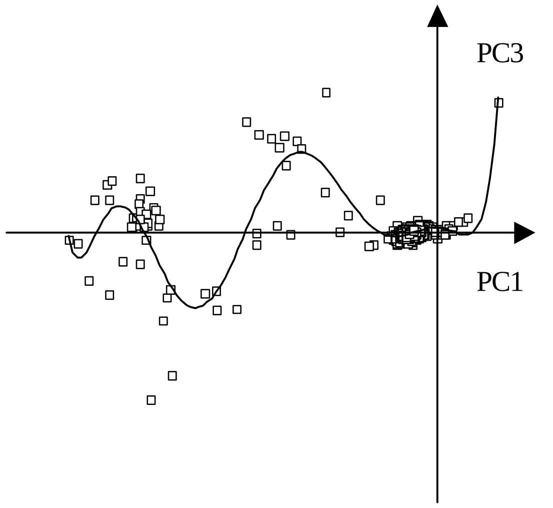


Fig. 1(c)
Third principal coefficient versus first principal coefficient for MIT-BIH record 205

~~Note that the 'shifted' energy is actually represented by the polynomials relating y_{i1} to y_{i2}' etc. as shown in Figure 2. Although the process could be extrapolated to multiple dimensions with likely improvement in compression performance, the multiple 2-D approach here is computationally more straightforward and efficient.~~

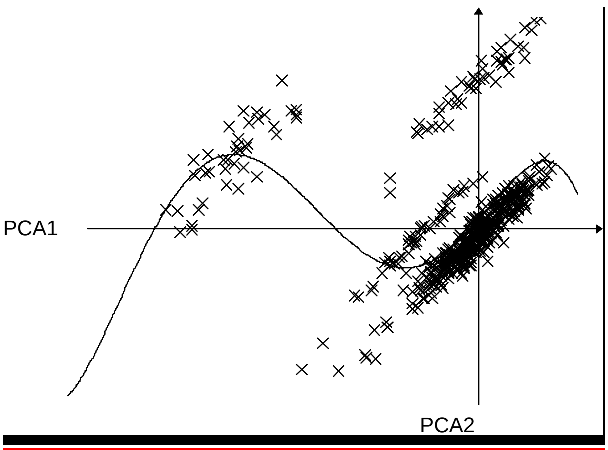
Storage requirements are reduced to a single transformed coefficient per beat plus an overhead– which is nearly negligible when amortised across a full set of beats.~~Typical total storage requirement consists of two parts. Firstly an overhead of eigenvectors and polynomials amortised over a full set of beats which may have several hundred or thousand members within it, and secondly a single byte per beat which is the first transformed coefficient, y_{i1}. To reconstruct an ECG,~~ Approximations to subsequent coefficients are calculated from the stored polynomials using the first coefficient in order to reconstruct the original waveform:

$$y_{i2}' = f_{1.2}(y_{i1})$$

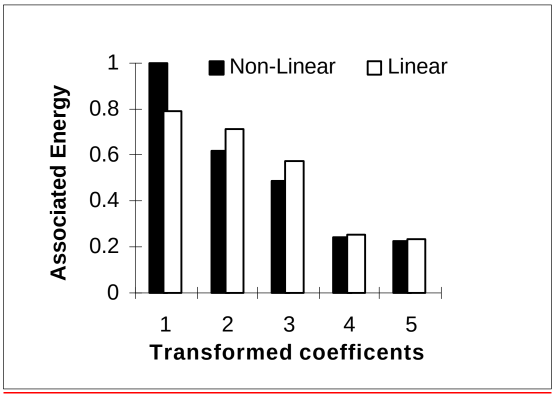
$$y_{i3}' = f_{1.3}(y_{i1}) \text{ etc.}$$

~~in order to reconstruct the original waveform.~~ From this point the reconstruction process is the standard inverse KLT as described in section 2 ($\boldsymbol{X_i = E^{-1}.Y_i + M}$) but using the *approximations* to the higher index coefficients. As with KLT, a reduced number of the linear basis vectors (eigenvectors) are still required for each approximated coefficient.

~~These (typically) fifth order polynomials form part of the compression system overhead.~~

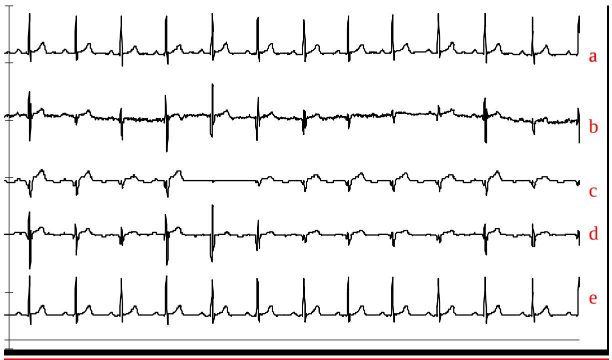


~~Fig. 1.Fifth order polynomial to capture energy relating PCA2 to PCA1 coefficient for sample MIT-BIH data set of 1000 beats.~~



~~Fig.2. Results of approximating four transformed coefficients (y_{i2}' to y_{i5}') with fifth order polynomials~~

~~From this point the reconstruction process is the standard inverse KLT as described in section II ($\boldsymbol{X_i = E^{-1}.Y_i + M}$) but using the *approximations* to the higher index coefficients. As with KLT, PCA compression, a reduced number of the linear basis vectors (eigenvectors) are still required for each approximated coefficient. Figure 3 shows the signals for the Figure 1 example (with means removed and amplitudes scaled up for clarity in Figure 3b, 3c, 3d).~~



~~Fig. 3. a) original ECG b) original minus mean (~x5 scale)~~
~~c) reconstructed difference from mean using one linear PC coefficient,(~x5 scale) d) as 'c)' but using estimated coefficients~~
~~e) reconstructed using estimated coefficient at 12bps~~

~~IV~~4. ANALYSIS

At present the scheme is optimised for exceedingly low bit rates at the expense of limited fidelity of reconstruction. Figure 3 shows the signals for the Figure 1(a) example (with means removed and amplitudes scaled up to emphasise any errors in reconstruction in Figure 3b, 3c, 3d). Figure 3d requires only four more bits per beat than Figure 3c but the non-linearity gives a substantial improvement in visual acceptability. In practice some signals provide less impressive results and work is continuing now to trade off some of the extra compression performance for improved fidelity of reconstruction across a broader spectrum of signals.

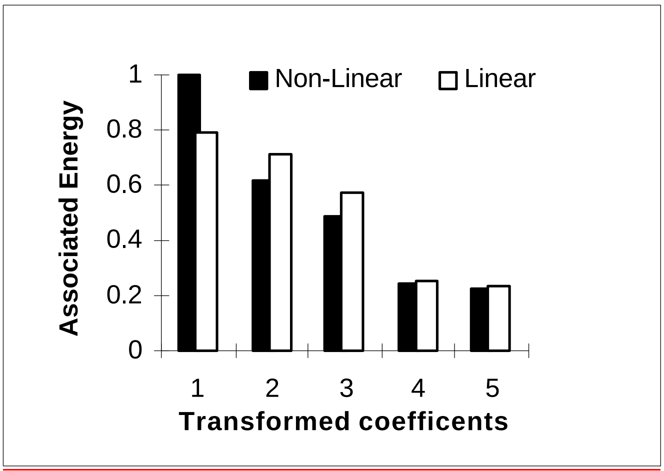


Fig.2.
Results of approximating four transformed coefficients (y_{i2}' to y_{i5}') with fifth order polynomials

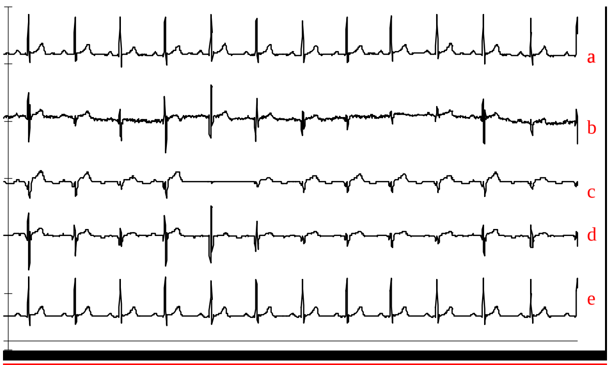


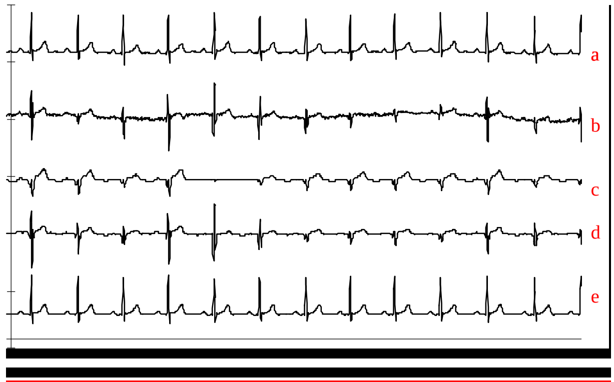
Fig. 3.
a) original ECG b) original minus mean (~x5 scale)
c) reconstructed difference from mean using one linear PC coefficient,(~x5 scale)
d) as 'c)' but using estimated coefficients
e) reconstructed using estimated coefficient at 182bps

In Figure 3 the reconstructed signal was based on compressed data equivalent to 18bps. This ~~This technique relies on the existence of non-linear correlations between successive axes.~~ **~~In practice, about one half of the subset of signals from the MIT-BIH database selected at random, showed improvements when measured using the crude but commonplace percent RMS difference (PRD) figure of merit, but all were subjectively better as demonstrated by the examples in Figure 4?????????????.~~** ~~The~~ 182bps ~~achieved~~ equates to a compression ratio ~~of~~ of 23640:1, starting from data sampled at 360Hz, 12 bit and includes the overhead. ~~This~~ It consists of 128 bytes for each (of three) basis vector; five coefficients for each (of three) polynomial using 8 bit approximations; the mean waveform of 128 bytes. The results shown in Figures 3 required a total overhead of (3*128*8) + (3*5*8) + (1*128*8) = 4216 bits, which amortises to 4 bits per beat over 1000 beats. –An additional 6 bit value for each beat is used to indicate the deviation from the expected temporal position of succeeding triggers. Finally the first principal component coefficient itself must be stored for each beat to give the 18bps total. ~~This~~ The overheads could be reduced further by applying standard compression techniques directly to these overhead elements, although this is not vital given that this bit rate equates to a compression ratio of 240:1, starting from data sampled at 360Hz, 12 bit and including the overhead.

Although only the first three eigenvector coefficients were employed or estimated for Figure 3, better results are obtained if a larger number of coefficients are estimated. This is particularly true where a number of beat morphologies are present in the recording. Most of the results obtained to date have involved storing the first coefficient and estimating coefficients two to ten, inclusive. Although this leads to slightly higher bit rates, the increase is not significant since it occurs through the storage of a greater overhead, which is amortised over the full set of beats.

-In practice it has been found that signals which include baseline wander give reconstruction errors which take the form of steps between beats. This is true of both KLT and the new technique. To overcome this, additional data is stored and a smooth transition from one beat to the next is calculated during the reconstruction. The additional data can take several forms. The simplest form stores a single average DC level for each beat. More sophisticated approaches that have been tried include storing the slopes and changes of slope throughout the beat. This amounts to an additional overhead ranging from 12 bits to approximately 40bits per beat. This overhead can be greater than the compression data itself and leads to bit rates of up to 60 to 70 bps for reasonable reconstruction quality where there is baseline wander. This facility could be selectively turned on and off leading to a minimal overall overhead as baseline wander tends to occur in limited sections of a long term recording. Figure 4 shows this type of error and the results of the improvement. Note that there are two distinct beat morphologies which the compression scheme has coped with in this example.

Fig. 4
I Original MIT-BIH trace 208
II Reconstruction from 25bps compression using estimate of higher order coefficients showing artefact between beats
III As per II but with boundary slope stored giving 55bps



~~Fig. 3. a) original ECG b) original minus mean (~x5 scale)~~
~~c) reconstructed difference from mean using one linear PC coefficient,(~x5 scale) d) as 'c)' but using estimated coefficients~~
~~e) reconstructed using estimated coefficient at 12bps~~

5~~V~~. CONCLUSIONS

One viable non-linear version of PCA has been derived which is restricted to employing the first principal component and polynomials to represent subsequent coefficients at minimal additional storage cost.

Limited testing with MIT-BIH[3] has shown that improvements over KLT are feasible with reduced quantitative PRD errors when a single transformed coefficient is stored with minimal overhead (Note that KLT normally uses several coefficients). This equates to a bit rate (previously only seen with stored template compression) of ~~less than~~ 1~~8~~2bps and is ~~two~~ more than an orders of magnitude lower than the Wavelet transform techniques[4] and substantially lower than Long Term~~tem~~ prediction[5] and ANN compression techniques[6] which both have better reconstruction performance but require around 100bps .

Visually acceptable representations of the ECG were usually obtained as seen in Figure 3, although some sets did not compress as well as others. Part of the variable performance observed on test recordings is explained by the requirement for the KLT orthonormal transformed axes to have some redundancy when non-linear relationships are sought, which might be true only in a subset of cases. Recordings with large baseline wanders were found to be reproduced more accurately by storing DC offset or slope information although if stored raw this could increase the bit rate several fold.

Future work will concentrate on extending the technique to give lower PRD for clinical measures by allowing more ~~non-linear principal~~ coefficients to be stored. The *extremely* low bit rate leaves scope for this approach which should maintain an advantage over linear KLT method using the same number of coefficients and operate with a wider range of ECG signals than at present.

REFERENCES

[1] M. Edward Womble, J. Halliday, S. Mitter, M. Lancaster, and J. Triebwasser, "Data compression for storing and transmitting ECGs/VCGs" *Proceedings of the IEEE*, Vol. 65(5), pp702--706, 1977

[2] J. Mathews, Numerical Methods for Computer Science, Engineering and Mathematics, Prentice Hall International, 1987.

[3] G. Moody, "MIT-BIH arhythmia database directory", MIT Division of Health Sciences and Technology, 3rd edition, BMEC TR010, July 1992

[4] J. Hall, J. Crowe, "Ambulatory Electrocardiogram Compression using wavelet packets to approximate the Karhunen-Loeve Transform", Applied Signal Processing, Vol.3, pp25-36, 1996

[5] Nave, A Cohn, 'ECG compression using long term prediction', IEEE transactions on biomedical engineering, Vol. BME-40, No. 9 pp.877-885, September 1993

[6] D C Thomson, D J Hamilton and W A Sandham, "Electrocardiogram compression using artificial neural networks", Int. J. Applied Signal Processing,* Vol 2 No. 1, Feb 1996