Briefly, in accordance with one embodiment, an approach to employing Matching Pursuits coding of data is described.
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MATCHING PURSUITS CODING OF DATA

Field of the Invention

This application pertains to the field of coding data, and more particularly, to the field of selection of bases for coding data using transforms and/or matching pursuits.

BACKGROUND OF THE INVENTION

Digital data for various forms of content, such as, without limitation, digital images, digital video, and/or audio information, is delivered today via wireless transmission networks, digital satellite services, streaming video and/or audio over the Internet and more. For example, again, without limitation, delivering video and/or audio content in a digital data form to personal digital assistants, cellular phones and/or other devices is continuing to increase in popularity. Therefore, a need continues for data compression and decompression techniques to allow efficient transmission and storage of digital data, regardless of the content the data represents.

BRIEF DESCRIPTION OF THE DRAWINGS

Subject matter is particularly pointed out and distinctly claimed in the concluding portion of the specification. Claimed subject matter, however, both as to organization and method of operation, together with objects, features, and advantages thereof, may best be understood by reference of the following detailed description if read with the accompanying drawings in which:

Figures 1-3 are plots illustrating sample results from applying an MP process to code data;

Figure 4 is a table of example bases provided for illustration purposes; and

Figure 5 is a table with an example mask provided for illustration purposes.

DETAILED DESCRIPTION OF THE INVENTION

In the following detailed description, numerous specific details are set forth to provide a thorough understanding of claimed subject matter. However, it will be understood by those skilled in the art that claimed subject matter may be practiced without these specific details. In
other instances, well-known methods, procedures, components and/or circuits have not been described in detail.

Some portions of the detailed description which follow are presented in terms of algorithms and/or symbolic representations of operations on data bits and/or binary digital signals stored within a computing system, such as within a computer and/or computing system memory. These algorithmic descriptions and/or representations are the techniques used by those of ordinary skill in the data processing arts to convey the substance of their work to others skilled in the art. An algorithm is here, and generally, considered to be a self-consistent sequence of operations and/or similar processing leading to a desired result. The operations and/or processing may involve physical manipulations of physical quantities. Typically, although not necessarily, these quantities may take the form of electrical and/or magnetic signals capable of being stored, transferred, combined, compared and/or otherwise manipulated. It has proven convenient, at times, principally for reasons of common usage, to refer to these signals as bits, data, values, elements, symbols, characters, terms, numbers, numerals and/or the like. It should be understood, however, that all of these and similar terms are to be associated with appropriate physical quantities and are merely convenient labels. Unless specifically stated otherwise, as apparent from the following discussion, it is appreciated that throughout this specification discussions utilizing terms such as "processing", "computing", "calculating", "determining" and/or the like refer to the actions and/or processes of a computing platform, such as a computer or a similar electronic computing device, that manipulates and/or transforms data represented as physical electronic and/or magnetic quantities and/or other physical quantities within the computing platform's processors, memories, registers, and/or other information storage, transmission, and/or display devices.

Matching pursuits processes may be used to compress one dimensional or multi-dimensional data, including but not limited to: still images, audio, video, and/or digital images. A matching pursuits process may include finding a full inner product between a signal to be coded and members of a dictionary of basis functions. At a position of an inner product, a dictionary entry giving an inner product may describe the signal locally. This may be the maximum inner product over all or part of the signal. This may be referred to as an "Atom." Amplitude may be quantized, and position, quantized amplitude, sign, and dictionary number may be combined to form a code describing a particular Atom, for example. For one embodiment, quantization may be performed using a precision limited quantization method.
Other embodiments may use other quantization techniques. Claimed subject matter is not limited in scope to any particular quantization method or technique. All potential quantization methods now known or to be developed are intended to be included.

In one particular embodiment, an Atom is subtracted from a signal giving a residual. The signal may be completely and/or partially described by the Atom plus the residual. The process may be repeated with new Atoms successively found and subtracted from the residual. At any stage, the signal may be completely described by the codes of the Atoms found and the remaining residual.

Matching pursuits (MP), therefore, may decompose any signal / into a linear expansion of waveforms that may belong to a dictionary \( D = \{ \varphi \} \) of basis functions, such that

\[
f = \sum_{n=0}^{\infty} a_n \varphi_m + R^m f
\]

where \( R^m \) is the \( m \)th order residual vector after approximating \( f \) by \( m \) 'Atoms' and

\[
a_n = \langle \varphi_m, R^m f \rangle
\]

is an inner product at stage \( n \) of a dictionary with an \( n \)th order residual, for this particular embodiment.

For some embodiments, a dictionary of basis functions may comprise two-dimensional bases. Other embodiments may use dictionaries comprising one-dimensional bases which may be applied separably to form two-dimensional bases. To do this, a selected basis function may be applied to a set of data in one of its dimensions and another basis function may subsequently be applied in another dimension, the remaining dimension if there are two dimensions. A dictionary of \( b \) basis functions in one dimension may provide \( b^2 \) combinations which form a dictionary of \( b^2 \) basis functions in two dimensions, for example. This may likewise be extended to any number of dimensions. Therefore, in this context, the term "separably" includes applying different basis functions to data separately.

As described in more detail hereinafter, a method is described which may reduce complexity of a codebook to be applied to coding of multi-dimensional data. Likewise, improved representation of the data may also at times occur. In this particular embodiment, a dictionary of \( n \) dimensional bases may be formed separably, as described above, for example, from a set of previously determined \( n \)D bases, although, of course, claimed subject matter is not limited in scope in this respect. A subset of a full \( n \) dimensional dictionary may be selected for coding data. In one particular embodiment, although claimed subject matter is not limited in
scope in this respect, this may be implemented using a mask to select a subset of a full dictionary. For images, as one example, for a range of numbers of selected bases for a bit rate, a PSNR may, at times, provide improved results in comparison with a full 2D codebook. As described in more detail hereinafter, results with sparse dictionaries, therefore, may have lower computational cost while maintaining data integrity to a high degree.

As is known, a dictionary may play a role in terms of speed for a particular method or process of compression. See, for example, Monro, D.M., "Basis Picking for Matching Pursuits Image Coding", EEEIE International Conference on Image Processing (ICIP 2004), Singapore, September 2004; Yuan Yuan and Monro, D.M., Improved Matching Pursuits Image Coding" IEEE International Conference on Acoustics, Speech and Signal Processing ICASSP 2005, Philadelphia, March 2005. However, a dictionary may also play a role in complexity and accuracy, as explained in more detail hereinafter.

For example, if the number of ID bases is $b$ and the basis width or 'footprint' is $d=(2w \cdot k +1)$, then in 2D there are $b^2$ bases. One aspect of a MP process includes repairing or updating inner products in a region of an Atom that has been removed from the data. This may involve calculation of inner products in a $d \times d = d^2$ region of the image. Even if done separably, one desire to compute inner products in a first dimension with bases in a 1D region of extent $2d-1$ for $b$ bases of width $d$, at a computational cost of order $bd^2$ followed by inner products in a second dimension in a 2D region of extent $2d-1$ by $2d-1$ for $b$ results of the first stage, using $b$ bases of width $d$, at a computational cost of order $b^2 d^3$. In this example, therefore, the second stage is more complex. In higher dimensions, the gain has the potential to be greater since complexity in $n$ dimensions may be proportional to $b^{N_c} f^{b^n}$.

In general, a large codebook may give a greater accuracy for a particular number of Atoms selected; however, it may also employ more bits to code an Atom from a larger codebook. Therefore, at a selected bit rate, for example, it may not give the greatest accuracy. As is well-known, reducing the codebook size by half may reduce the bit cost of coding an Atom by 1 bit in the case where all bases are equally likely. More particularly, the cost of coding any of $n$ equally probable symbols is well-known to be $\log_2 N$. Although typically probabilities of occurrence of the bases will, in general, not be equal, a similar effect may occur if the probabilities do not vary widely. Thus, a reduction in the cost of coding may occur as dictionary size is reduced. By trimming an $n$ dimensional codebook, one may accomplish a beneficial rate/distortion trade-off, e.g., a lower distortion at a given rate or a lower bit rate for a given distortion.
In one particular embodiment, a reduced dictionary may be implemented as a mask applied to a full n dimensional dictionary by indicating which bases are to be applied. By referring to this mask, bases from a separable codebook may be selected to perform inner product calculations in a Matching Pursuits (MP) process, or applied to the data in other coding applications. For such an embodiment, while all bases may in some embodiments be considered in a first stage operation of separable computation, not all combinations are used in the second dimension, and fewer still are used in higher dimensions, potentially reducing the number of calculations. This complexity reduction has the potential to make computations feasible, especially for higher dimensional coding tasks that previously may not have been feasible. Likewise, in other embodiments, less than all bases may be considered as well in a first operation, for example. These embodiments are merely intended as illustrative examples; however, many other embodiments are intended and contemplated to be including within the scope of claimed subject matter.

A resulting dictionary may be used on a signal, or data that has been transformed, such as by a wavelet transform. Furthermore, a final dictionary may be utilized to code data with an MP process. This process may also be used with other data, including audio, visual, video, multi-dimensional, and/or non-transformed data. Furthermore, a resulting dictionary may be used to code many different types of transformed and/or non-transformed data. Yet further, an embodiment of a method and/or system, for example, within the scope of claimed subject matter, may be utilized to determine resulting dictionaries and/or codebooks for many different types of data coding.

For compression, for example, an MP process may be terminated at some stage and codes for a number of Atoms may stored and/or transmitted by a further coding process. For one embodiment, the further coding process may be a lossless coding process, although claimed subject matter is not limited in scope in this respect. Other embodiments may use other coding techniques, including non-lossless coding techniques, for example.

Therefore, as will become clearer, not every basis is necessarily effective for image coding in a separable basis dictionary for Matching Pursuits (MP), so that a subset of bases may, in some instances, provide improved PSNR while also reducing computational complexity.

To provide further background, MP was introduced by Mallat and Zhang for digital audio. See, for example, S.G. Mallat and Z. Zhang, "Matching pursuits with time frequency dictionaries", IEEE Trans. Signal Processing, vol. 41, pp. 3397-3415, Dec. 1993. Later, Neff and

For this particular embodiment, to illustrate, a hybrid wavelet/MP codec is employed, although claimed subject matter is not limited in scope in this respect. Again, this is merely provided as an illustrative example. For coding, a multi-scale wavelet decomposition, for example, may be applied using the well-known bi-orthogonal 9/7 filter bank before MP approximation, although, of course, claimed subject matter is not limited in scope in this respect. It has been shown, for example, that 2 scales for CIF (352 x 288) residuals and 5 scales for D1 (704 x 576) still images are a good choice, although, again, this is merely an illustrative example and is not intended to limit the scope of claimed subject matter.

Atoms for MP may be found directly on a 2D wavelet coefficient array using a dictionary of 2D bases. In MP coding, a dictionary of basis functions is typically repeatedly searched for an inner product of largest magnitude within a data set. In 2D, however, it is usual to take a dictionary as a set of 1D bases applied separably, as described above, for example. The bases for this particular embodiment comprise an over-complete, non-orthogonal set of Gabor functions, defined by

\[ g_k = \left( \exp \left( -\frac{\pi t^2}{\varphi_k} \right) \right)^{0.25} \cos \left( \frac{\pi f_k l t}{w_k} + \varphi_k \right) \]

where the dictionary index is \( k \) and \( t \in \left[ W_k, ..., W_k \right] \). Maximum width ('footprint') \( (2W_k + 1) \) is \([3,5,7,9, ...]\). Basis frequencies \( f_k \in [0,1,...,W_k] \) Phase shifts \( \varphi_k \in [(0,0.5,1.0,1.5,2.0) \pi/4] \) Attenuation factors \( \sigma_k \in [1,2,4,8,16,24,24] \)

Figure 4 below has a table (Table 1) that lists bases examined in the article, D.M. Monro and Yuan Yuan, "Bases for low complexity matching pursuits image coding", IEEE Int. Conf.
Image Process., Sept. 2005, with width d = 9. Claimed subject matter is not limited in scope to these bases; however, out of convenience, these are provided here for illustration purposes. The first 8 bases were recommended for coding residual images (e.g., Displaced Frame Difference, DFD or inter-frames) and the 14 bases for still images (e.g., intra frames).

For this particular embodiment, a subset of a full 2D dictionary may be formed. This may be done for this particular embodiment by introducing a mask into the coding process containing a zero value corresponding to a basis that is not used. Beginning with a completely zero mask, for example, a basis may be used in turn to code a training set on its own. The basis giving the highest PSNR at a desired bit rate, for example, may be selected as a first unmasked dictionary entry. With a first basis determined, a test set may be coded with combinations of this first basis with one other basis, and the highest in terms of a defined performance measure, for example, may then be added to the dictionary to become the second unmasked entry for further runs, etc. The process may be repeated until the mask is fully populated. The result is a pruned sparse 2D dictionary of every size from 1 to the maximum. This process is similar to the basis picking method for selecting ID bases, discussed in D.M. Monro, "Basis Picking for Matching Pursuits Image Coding", IEEE Int. Conf. Image Process, Singapore, October 2004, although, of course, claimed subject matter is not limited in scope in this respect.

An example of a mask is given in Figure 5 (Table 2) below, in which this mask gives the highest average PSNR across a range of bit rates on Gold Hill (BestAvGh), as described below. In the table, the nonzero numerals indicate the order in which the bases were unmasked, so that by reference to it a codebook of size up to 119 may be determined from the table.

Successive basis masking, of course, may be a computationally intensive process. However, in some embodiments, it may be used to design a masked dictionary and, therefore, may be used in many applications after computation, although claimed subject matter is not limited in scope in this respect. With a 14 x 14 dictionary used for coding still images, for example, selecting a first basis involves coding a training set 196 times. Finding a second basis involves 195 runs and so on, so that the total number of runs in this particular example is 19305. As one example, for still images, the Gold Hill luminance (Y) 704 x 576 image was used as a training set, similar to how it was used to select the ID bases in the previously cited article, "Basis Picking for Matching Pursuits Image Coding," although, again this is merely an illustrative embodiment and is not intended to limit the scope of claimed subject matter. For
motion compensated residuals (e.g., inter-frames), a residual from the Foreman sequence was used, of size 352 x 288 pixels.

For training still image Gold Hill, Figure 1 shows the PSNR at a bit rate of 0.4 bits/pixel (bpp) as bases are progressively unmasked. As the codebook grows in size, more bits are employed to code the dictionary entries, so the number of bases coded at a fixed bit rate decreases. The PSNR increases until, with 19 bases, it reaches a value better than the PSNR obtained with a full codebook of 196 bases. It then oscillates about similar values as the codebook size increases by progressive unmasking. [The highest PSNR is with 54 bases unmasked. In Figure 2, similar behavior is shown at a reduced scale for several bit rates. It is seen that the behavior of sparse dictionaries is similar at the other bit rates examined in this example. Likewise, the PSNR declines as the size of a full dictionary is approached. Figure 3 shows the PSNR as the dictionaries are built for a residual training set, with similar behavior as the bases are unmasked. In these examples, the PSNR obtained using a full codebook is exceeded with a relatively small numbers of bases.

These examples show that a sparse subset of a full 2D separable MP codebook may provide higher PSNR at lower complexity than a full codebook, at least at times. Not surprisingly, masks found at low bit rates tend to work better at low bit rates and those found at high bit rates tend to work better at high bit rates. A masked codebook may in some instances, at least, be found which may provide improved overall PSNR performance.

Of course, as may be appreciated, a dictionary may be described implicitly or explicitly. For example, a functional form or a curve or surface may be specified. Thus, supplying parameters rather than pre-computed basis functions may be employed. A dictionary entry, for example, may be communicated as sampled values of a function. Likewise, a dictionary entry may be communicated as parameters from which a function is capable of being computed. Of course, these are merely examples and claimed subject matter is not limited in scope in this respect.

Likewise, in other alternate embodiments, multiple dimensions, such as three spatial dimensions may be employed. In one such example, a 3D MRI Scan, or a 3D map of the temperature of the ocean or of the atmosphere or of any data or measurement describing a volume may be compressed. Likewise, alternately, a third dimension might be time. Likewise, an embodiment may employ four dimensions, such as, for example, a 3D spatial image and time. More than four dimensions may also be possible as, for example, if there is a relationship
between temperature and density plus three spatial dimensions plus time. These are merely illustrative examples and many other embodiments of multiple dimensions are included within the scope of claimed subject matter. Likewise, in some embodiments, data may comprise multiple dimensions even if they might or might not be formed separable from lower dimensional bases. In this case a subset of all the possible bases might be used and a multiple dimension mask might be used to indicate which bases are used.

It will, of course, be understood that, although particular embodiments have just been described, the claimed subject matter is not limited in scope to a particular embodiment or implementation. For example, one embodiment may be in hardware, such as implemented to operate on a device or combination of devices, for example, whereas another embodiment may be in software. Likewise, an embodiment may be implemented in firmware, or as any combination of hardware, software, and/or firmware, for example. Likewise, although claimed subject matter is not limited in scope in this respect, one embodiment may comprise one or more articles, such as a storage medium or storage media. This storage media, such as, one or more CD-ROMs and/or disks, for example, may have stored thereon instructions, that when executed by a system, such as a computer system, computing platform, or other system, for example, may result in an embodiment of a method in accordance with claimed subject matter being executed, such as one of the embodiments previously described, for example. As one potential example, a computing platform may include one or more processing units or processors, one or more input/output devices, such as a display, a keyboard and/or a mouse, and/or one or more memories, such as static random access memory, dynamic random access memory, flash memory, and/or a hard drive.

In the preceding description, various aspects of claimed subject matter have been described. For purposes of explanation, specific numbers, systems and/or configurations were set forth to provide a thorough understanding of claimed subject matter. However, it should be apparent to one skilled in the art having the benefit of this disclosure that claimed subject matter may be practiced without the specific details. In other instances, well known features were omitted and/or simplified so as not to obscure the claimed subject matter. While certain features have been illustrated and/or described herein, many modifications, substitutions, changes and/or equivalents will now occur to those skilled in the art. It is, therefore, to be understood that the appended claims are intended to cover all such modifications and/or changes as fall within the true spirit of claimed subject matter.
WHAT IS CLAIMED IS:

1. A method comprising:
   coding multi-dimensional data using a codebook of basis functions;
   wherein said codebook comprises a subset of a larger multi-dimensional basis
   dictionary, said larger dictionary comprising separable combinations of one or more
   primary one dimensional basis function dictionaries.

2. The method of claim 1, wherein said one or more primary one dimensional basis
   dictionary or dictionaries are communicated to a decoder.

3. The method of claim 2, wherein a primary dictionary entry is communicated as sampled
   values of a function.

4. The method of claim 2, wherein a primary dictionary entry is communicated as parameters from which a function is capable of being computed.

5. The method of claim 1, wherein data indicative of the subset to be used is communicated
   to a decoder.

6. The method of claim 5, wherein the subset is described by a mask that is applied to a
   larger dictionary.

7. The method of claim 5, wherein the subset is described by data indicative of selected
   entries of said larger dictionary.

8. The method of claim 1, wherein said data and said dictionary are two dimensional.

9. The method of claim 8, wherein said two dimensional data comprises a digital image.

10. The method of claim 1, wherein said data and said dictionary are three dimensional.

11. The method a claim 10, wherein two of the three dimensions are spatial and the third
    dimension is temporal.

12. The method of claim 10, wherein the three dimensions are spatial.
13. The method of claim 1, wherein said data and said dictionary are of more than three dimensions.

14. The method of claim 13, wherein one of the dimensions is temporal.

15. The method of claim 1, wherein the data dimension is higher than the codebook dimension; and wherein a Matching Pursuits process is applied to lower dimensions of the data.

16. The method of claim 1, wherein a transform is applied to said data in at least one dimension prior to application of a Matching Pursuits process.

17. The method of claim 16, wherein said transform comprises a wavelet transform.

18. The method of claim 17, wherein said transform comprises a Discrete Cosine Transform.

19. A method comprising:
   decoding multi-dimensional data using a codebook of basis functions; wherein said codebook comprises a subset of a larger multi-dimensional basis dictionary, said larger dictionary comprising separable combinations of one or more primary one dimensional basis function dictionaries.

20. The method of claim 19, wherein said one or more primary one dimensional basis dictionary or dictionaries are communicated to a coder.

21. The method of claim 20, wherein a primary dictionary entry is communicated as sampled values of a function.

22. The method of claim 20, wherein a primary dictionary entry is communicated as parameters from which a function is capable of being computed.

23. The method of claim 19, wherein data indicative of the subset to be used is communicated to a coder.

24. The method of claim 23, wherein the subset is described by a mask that is applied to a larger dictionary.
25. The method of claim 23, wherein the subset is described by data indicative of selected entries of said larger dictionary.

26. The method of claim 1, wherein said data and said dictionary are two dimensional.

27. The method of claim 26, wherein said two dimensional data comprises a digital image.

28. The method of claim 1, wherein said data and said dictionary are three dimensional.

29. The method of claim 28, wherein two of the three dimensions are spatial and the third dimension is temporal.

30. The method of claim 28, wherein the three dimensions are spatial.

31. The method of claim 1, wherein said data and said dictionary are of more than three dimensions.

32. The method of claim 31, wherein one of the dimensions is temporal.

33. The method of claim 1, wherein the data dimension is higher than the codebook dimension; and wherein a Matching Pursuits process is applied to lower dimensions of the data.

34. The method of claim 1, wherein a transform is applied to said data in at least one dimension prior to application of a Matching Pursuits process.

35. The method of claim 34, wherein said transform comprises a wavelet transform.

36. The method of claim 35, wherein said transform comprises a Discrete Cosine Transform.

37. An article comprising: a storage medium having stored therein instructions that, if executed, result in: coding multi-dimensional data using a codebook of basis functions; wherein said codebook comprises a subset of a larger multi-dimensional basis dictionary, said larger dictionary comprising separable combinations of one or more primary one dimensional basis function dictionaries.
38. The article of claim 37, wherein said instructions, if executed, further result in: one or more primary one dimensional basis dictionary or dictionaries being communicated to a decoder.

39. The article of claim 38, wherein said instructions, if executed, further result in: a primary dictionary entry being communicated as sampled values of a function.

40. The article of claim 39, wherein said instructions, if executed, further result in: data indicative of the subset to be used being communicated to a decoder.

41. The article of claim 40, wherein said instructions, if executed, further result in: the subset being described by a mask that is applied to a larger dictionary.

42. The article of claim 40, wherein said instructions, if executed, further result in: the subset being described by data indicative of selected entries of said larger dictionary.

43. An article comprising: a storage medium having stored therein instructions that, if executed, result in: decoding multi-dimensional data using a codebook of basis functions; wherein said codebook comprises a subset of a larger multi-dimensional basis dictionary, said larger dictionary comprising separable combinations of one or more primary one dimensional basis function dictionaries.

44. The article of claim 43, wherein said instructions, if executed, further result in: said one or more primary one dimensional basis dictionary or dictionaries being communicated to a coder.

45. The article of claim 43, wherein said instructions, if executed, further result in: data indicative of the subset to be used being communicated to a coder.

46. The article of claim 43, wherein said instructions, if executed, further result in: the subset being described by a mask that is applied to a larger dictionary.

47. The article of claim 43, wherein said instructions, if executed, further result in: the subset being described by data indicative of selected entries of said larger dictionary.
FIG. 1

TRAINING IMAGE GOLD HILL

PEAK SIGNAL TO NOISE RATIO (PSNR) dB

BASES SELECTED

0  20  40  60  80  100  120  140  160  180

33.2
33.1
33
32.9
32.8
32.7
32.6
32.5
32.4
32.3
PRUNED CODEBOOKS AT VARIOUS BIT RATES
TRAINING IMAGE GOLD HILL

PEAK SIGNAL TO NOISE RATIO (PSNR) dB

BASES SELECTED
○ 0.5 bpp
+ 0.4 bpp
× 0.3 bpp
◇ 0.2 bpp
□ 0.1 bpp

FIG. 2
PRUNED CODEBOOKS AT VARIOUS BIT RATES
TRAINING IMAGE FOREMAN RESIDED

PEAK SIGNAL TO NOISE RATIO (PSNR) dB

BASE SELECTED
○ 0.25 bpp
↓ 0.20 bpp
× 0.15 bpp
◊ 0.10 bpp
□ 0.05 bpp

FIG. 3
### FREQUENCY

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**TABLE 1**

**FIG. 4**