Towards holistic chromatic intelligent monitoring of complex systems

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Abstract

Purpose – To introduce chromatic methods and their application to monitoring complex systems.

Design/methodology/approach – Complexity is introduced and the need for holistic monitoring is suggested. The chromatic methodologies are introduced and their broad-ranging applicability is illustrated with reference to a number of diverse applications.

Findings – The generic chromatic monitoring technology has much to offer as a way of visualising, understanding, monitoring and controlling complex processes and system behaviour.

Practical implications – The technology is leading to new ways of characterising and evaluating aspects of system behaviour, in a holistic and non-intrusive manner, that are difficult to measure – e.g. walking behaviour of the elderly, tiredness of drivers.

Originality/value – Draws out the generic basis of the chromatic methodology and how it may be applied to a wide range of complex systems and situations to predict when and where human intervention is required.

Keywords Control systems, Image processing, Colour

Paper type Research paper

1. Introduction

Human-kind has a natural instinct to progress by expanding knowledge and understanding of natural phenomena and by developing technology to harness resources – a scientific, engineering and technology drive. One tool that serves particularly well in this endeavour is the concept of a system for referring to and delineating entities and phenomena in the world together with their interactions (Checkland, 1984). Natural systems may be viewed analytically in terms of their constituent elements in an infrastructure of biology, chemistry, physics and mathematics. Additionally, they are being viewed as emergent, synthetic, complex entities (Paton, 1997) with different behaviour and functionality emerging at each level in the hierarchy, for example, the cell, the organ, the organism, and the society. Complex natural systems, for example, weather, tend to occur in (or be) dynamical, non-linear, chaotic environments and are subject to unpredictability at the edge of chaos (Lewin, 1993; Mitchell Waldrop, 1992) whilst following certain laws and also attractors. Complexity similarly occurs in human social systems, where behaviour is subject to human laws, codes and customs (culture) to a large extent, as well as to natural instincts and the laws of physics.

The complexity that is being found in nature and natural systems is increasingly applying to man-made systems, where technology is designed for the purposes of reliably providing products or services with a high level of automation in a planned and controlled manner – for example, the electricity grid. Complex man-made systems characteristically have order and stability but there are possibilities that they may be drawn into a chaotic regime and into failure modes in unforeseen ways, for example, the California electricity supply system, and the requirement for manual control of the UK national grid at peak times, which imply that moving towards more local generation and supply would be beneficial. Furthermore, evaluating the state of health of complex systems from the instantaneous values of a number of system parameters is also difficult given that there are, potentially, unpredictable failure modes that may not be taken into account since the combinations of parameter values are too numerous to consider in their entirety and systems do not operate in isolation.

Generally, whether the system is natural, or is man-made and provided with fault tolerance and self-regulation, some level of direct human monitoring and, ultimately, intervention in the system, is required. In the case of man-made systems, this...
ranges in immediacy and frequency from ad hoc to regular inspection of the system and system data, and from scheduled maintenance to manually overriding controls. Different scenarios could be envisaged for the future in this regard although, for example, currently, and for the foreseeable future, planes carry real human pilots for very good reasons.

The technology drive has a further implication with respect to the requirements for monitoring. It fuels opposing tendencies that need to be reconciled – on the one hand, the tendency towards greater system intelligence and autonomy (freeing humans from supervision and intervention at some levels) and, on the other hand, towards increasing complexity and potential unpredictability (requiring increased expert human supervision, especially for rare and unusual, but major, events). Arguably, the gap between these tendencies can be bridged through intelligent monitoring systems that can be applied to the whole monitored complex system – holistically – to assess and assure overall system behaviour. Desirable features of intelligent monitoring systems are that they address the whole system, with information fusion from all available sensor data; are proactive and prognostic; are interactive in supporting the human expert/operator and can be queried when necessary; are non-intrusive, and thereby are easily retro-fitted; and are generically applicable, including the capability for using naturally available data about the system, e.g. from ambient acoustic, vibration, temperature, colour, radio-frequency information, as well as data from sensors specifically introduced, or even from existing dial readings, in order to maximise cross-correlation of information on system status.

When considering the whole system, a traditional array of sensors may not be sufficient to ascertain overall system health and behaviour, representing instead a selection of possible symptoms. Furthermore, as noted, a holistic approach may make use of naturally occurring information such as patterns in the acoustic, temperature, light, infra-red, electro-magnetic, radio-frequency, etc. domains to complement an existing sensor array, or may even derive additional information from existing sensor data. For example, the centre of gravity of an airplane in flight, which cannot be measured directly, may be deduced from other sensor data used as indirect indicators. Also, in health care, for example, temperature (normally self-regulating through homeostatic mechanisms) is an important indicator of health and is one of a range of vital signs, but a doctor (a system administrator) takes into account a vast amount of other, predominantly visual (and also verbal) information before considering temperature, aiming to perform an overall health check (an assessment of system behaviour). The aim is to check and remediate any existing problems (diagnosis) and, in so doing, to anticipate and prevent further problems (prognosis) before they require emergency intervention. Often by the time an alarm occurs it is too late to remediate. For example, in the case of the elderly living alone, one of the keys to health and well-being is the overall temperature of the person’s environment affecting their personal temperature, not just the temperatures at a number of points within the environment, which fluctuate and may be significantly divergent. To obtain personal temperature data may be inconvenient, intrusive and not timely. Rather, reassurance is sought as to the person’s normal movement and behaviour to supplement available temperature data. Under the holistic approach, normal (or planned) complex system behaviour may be viewed and defined as that which occurs within specific bounded regions (occurring before the chaotic regions) of trajectories of system behaviour.

The present contribution details and illustrates the chromatic approach (Jones et al., 2000, 2003) to intelligent monitoring of complex systems. It is demonstrated that chromatic processing is analogous to human vision whilst extending far beyond the visible part of the spectrum and to other domains such as the acoustic. The approach and its capabilities are illustrated here and throughout the session with examples of graphical polar plots, which may depict, for example, process life cycles, some having “centres of gravity”. The examples are drawn from diverse areas such as domiciliary and neonatal monitoring; the balance of gases during an anaerobic digestion cycle; high voltage transformer gases; balances of pollution gases and particulates by day of the week, by time of day, by month, and their intersection; and railtrack monitoring plots.

2. Chromatic processing

Colour (in Greek khroma) is a very useful physical dimension in human life and it may also be used in a metaphorical sense, for example, to describe different particle types in quantum chromodynamics and chromatic scales. Chromatic intelligent monitoring also relates to vision and optics, both literally and metaphorically. Physically, human vision is based on rods and cones in the eye (sensors and filters) responding to visible light of different wavelengths (colour) to provide signals conveying information in terms of the primary colours red, green and blue. In connection with information, the concept of vision is also generally used in a metaphorical sense, for example, in terms of data visualisation, information picture, supervision, and zooming to different scales and levels. Being based on colour science, chromatic processing applies physically to signals and metaphorically in the information domain to aid in the interpretation of the significance of the signals. Figures 1 and 2 shown the combined approach.

With reference to Figure 1, the information in the signal is abstracted – and compressed – by the application of three filters, here with Gaussian responses, as those of the human eye when acquiring red, green and blue wavelengths. Owing to the similarity with human vision, the chromatic filters are referred to simply, and arbitrarily, as $R$ (red), $G$ (green) and $B$ (blue). The responses (filters) are overlapping. This non-orthogonality enhances sensitivity to changes in the overlapping regions. As a result of chromatic processing with $R$, $G$ and $B$ filters, a complex spectrum may be characterised by just three values, those of $R$, $G$, and $B$.

Figure 1 Acquisition and chromatic processing of an arbitrary signal (e.g. a light spectrum in the wavelength domain)
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Figure 2 Information representation in HLS colour space

![Hue, Lightness, Saturation](image)

G and B. The RGB colour space is a cube. On the diagonal of the cube from RGB (0, 0, 0) to RGB (1, 1, 1), R = G = B, which means that there is no dominant colour out of R, G and B. This line represents greyscale, starting at black (no light, \( R = G = B = 0 \)) and finishing at white (maximum \( R, G \) and \( B \); \( R = G = B = 1 \)). The RGB cube may be transformed via algorithms from colour science into other representations that emphasize different relationships emerging from the relative proportions of \( R, G \) and \( B \), for example, the HLS representation (hue, lightness and saturation) (Jones et al., 2000).

Figure 2 shows the diagonal greyscale line as the central axis of a double hexagonal cone shape. The energy or intensity of the signal, known as lightness (\( L \)), is depicted on the central axis and ranges from 0 (black, no light) to 1 (white, maximum RGB). In the domain of vision, lightness is equivalent to brightness. The circumference of the hexagonal cone identifies the region of dominant colour (red, green, blue, or intermediate hues of yellow, magenta and cyan, etc.). This identifier of the dominant colour is known as hue (\( H \)). The radius extending from the central axis out to the circumference of the cone serves to identify the saturation (\( S \)) of the colour. Locations that are nearer the central axis are low in saturation (the spread of values – the bandwidth – between \( R, G \) and \( B \) is low) whereas locations on the outer circumference identify pure colour – here, one of \( R, G \) or \( B \) is maximum with one or both of the other two equal to 0. The original raw signal may now be considered and characterised in terms of its dominant wavelength (hue), its bandwidth (saturation) and its intensity (lightness) in the information domain, independently of the physical meaning of the signal.

Another advantage of the HLS representation is its close relationship with normal statistical distributions, with \( L \) representing the amplitude (energy) of the distribution, \( S \) its standard deviation and \( H \) the location of the distribution.

A further advantage of the HLS representation is that hue-saturation (HS)/hue-lightness (HL) values may be conveniently represented on polar plots, as illustrated subsequently and throughout this session. The polar plot representation is well suited for visualising and tracking system behaviour and for depicting the fusion of information about the monitored system from multiple sensors, using algorithms from colour science (Brazier et al., 2001a). Naturally, the patterns that are formed in HLS space to characterise system behaviour may also be quantified, for example, in terms of event probabilities (Zhang et al., 2005).

Examples of chromatic processing are presented, including visual monitoring (e.g. of neonatal patients for bilirubin, of thermochromic patches for temperature); acoustic monitoring (railtrack); anaerobic life cycle gas production; and data representation and visualisation (pollution monitoring).

### 3. Examples of chromatic monitoring applications

The first example, neonatal monitoring, illustrates predominantly visual monitoring, with support for remote access (Brazier et al., 2001b).

#### 3.1 Neonatal bilirubin monitoring

Figure 3 shows an application of direct visual monitoring of a neonatal patient’s skin colour using a CCD camera image and extracting HLS information directly from the RGB pixels in the image. Hue represents skin colour (increased yellowness indicating raised bilirubin levels associated with jaundice; blueness indicating blood oxygenation condition; and redness indicating blood circulation condition). Constant non-intrusive surveillance of patient colouration is provided to give advanced warning of any change in bilirubin level between bilirubin analyses which are acquired from blood samples obtained once a day intrusively. The surveillance may be automated and may be remotely accessible, for example, via web technology, which can also provide a useful additional method of access for parents in between visits. Figure 3 also shows the use of thermochromic temperature patches, which change colour with temperature and thereby provide a non-intrusive and simple access to temperature information at the same time. Acoustic information may also be included.

#### 3.2 Railtrack monitoring

Figure 4 shows a complex acoustic signal acquired by microphone mounted on a train to record acoustic signals emanating from the wheel-rail interface of the train. The aim is to detect actual track faults, to warn of faults that may be developing and to characterise the track condition. A polar plot of the \( H-L \) parameters for this section of track is shown in Figure 5 which shows a number of outlying points that represent different kinds and intensities of fault, ranging from squats and wheelburns to higher frequency events such as rolling contact fatigue. The condition of the track generally is reflected in the location of the majority of the signal on the \( H-L \) plot.

Figure 3 Visual neonatal monitoring

![Visual neonatal monitoring](image)
Figure 4 Acoustic signal from railtrack

Figure 5 Acoustic monitoring of railtrack
3.3 Anaerobic digestion monitoring

Figure 6 shows an example of a polar plot being used for process tracking. Here, the $R$, $G$ and $B$ inputs to the $H$-$S$ plot are relative proportions of gases involved in an experimental, industrial-scale anaerobic digestion process. The gases of interest are the principal starting components of air, i.e. nitrogen ($N_2$, neutral to the process but indicating the presence of air), oxygen ($O_2$, harmful to the process), argon ($Ar$, neutral indicating presence of air), and the main outputs of interest, $CO_2$ and $CH_4$ (methane); $H_2O$ and $CH_3$ are additional, less relevant indicators of activity. The $R$, $G$, $B$ filters acquire the relative proportions of the gas flows with the gases of interest arranged in ascending order of interest through the process. The single green line from the right side (air) across to the left side ($CO_2$) through to $CH_4$ and then to the centre of the plot (no flow activity) represents the ideal gas composition that occurs throughout an anaerobic digestion cycle from its start (air), through to generating the output gases $CO_2$ and $CH_4$, then to non-activity. The more “noisy” line (red) that starts near the centre (no activity) then progresses through similar stages as the ideal curve, going to the centre on several occasions, represents an actual anaerobic digestion cycle, which followed the ideal curve quite closely but leaves room for further optimisation. The actual curve went to the centre on a number of occasions because the lid was opened, letting in air which inhibits the process activity until the oxygen has been purged. This illustrates how potential faults (e.g. air ingress due to a leak in the lid seal) may be tracked in addition to the general “state of health” of the process and planned interventions (e.g. deliberate lid opening).

3.4 Pollution monitoring

Figure 7 shows an example of polar plots being used in a “spatial” dimension. Here, the $R$, $G$ and $B$ inputs to the $H$-$L$ plot are the levels of $SO_2$, $NO_2$ and $PM_{10}$ (particulates less than 10 $\mu m$ in diameter), which are the main components of airborne pollution, recorded over a six month period in the same location in the North-West.

Different colours represent different time periods during the day and the inputs are normalised to the centre of the plot. The Hue angle indicates which component of the three dominates at any time and the lightness represents the overall level of the three components that may rise and fall. The period 19:00-24:00 tends to produce the highest values all round ($\geq 2$ standard deviations). There is a tendency for $PM_{10}$ and $NO_2$ to be particularly predominant in the evening (19.00-24.00) and a bit quieter during the morning (00:00-06:00 and 06.00-10.00). The period 10:00-16:00 tends to be more dominated by $SO_2$ alone. These components are particularly related to vehicle exhausts and traffic flow is expected to play a major role in the timings, balance and composition of the mixture. All three components are involved in the higher levels that occur during the afternoon from 16.00 to 19.00, again related to increased traffic flow. The data may also be plotted by month and by day of the week. Looking at intersections of the three polar plots can give further insight into the nature of the complex patterns of airborne pollution.

4. Discussion

The aim of this contribution is to give an illustrated overview of some of the key uses of the generic chromatic technology.
for monitoring complex systems. Some of the main functions and capabilities it provides are now summarised. The first two, “supervision” and “view”, relate to the visual sense of monitoring and “seeing” data.

**Supervision**
Different levels of organization (or different domains) of system behaviour may be consolidated using the same technology (e.g. polar plots) in an embedded sense, providing an overall, holistic information “picture”. This is analogous to, and may be converted into, top-level information, such as a red/amber/green status for overall system behaviour, which is abstracted from the complex, fuzzy world to enable decision-making. There are parallels here with, for instance, an operator’s or pilot’s view. Simon (1957) refers to decision-making on the basis of incomplete or uncertain information as “satisficing”, which is decision-making based on using available information, whether it is complete or not, to reach a decision. Chromatic monitoring goes beyond this, having extracted the essential information from the complex web of data that is available, whilst retaining traceability of significant information extracted at source in case it is needed for subsidiary views. By analogy, the pilot focuses on the main top-level indicators to assess overall system health such as speed, direction, altitude, attitude, location and fuel availability, but has access to further, specific, more minor instruments and data, that expand on or support the higher levels, if needed.

**View**
Chromatic monitoring has the capability for zooming in to micro scales for fine detail (e.g. local weather) or out to the whole system behaviour (e.g. regional, global weather patterns, global timescales) as required, accomplished in part through filter design.

**Tracking**
Monitoring system behaviour against plan or expectation or for abnormal behaviour, which may be applied to theoretical or empirical (or hybrid) system models. This is an extension of supervision in that ideal or expected system behaviour is already known and may be incorporated into the monitoring, e.g. as a behaviour trajectory on the polar plot. It is then possible to predict when intervention in the system is required.

**Statistics**
With filters based on Gaussian characteristics and the Gabor transform basis, the chromatic analysis effectively compares the data to statistical distributions (e.g. the normal distribution), with $H$ equivalent to the mean, $S$ equivalent to the variance and $L$ equivalent to amplitude (energy). In particular, rare but potentially catastrophic events, that may
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occur in the “tails” of the normal distribution are amplified by means of the overlapping filters, which can perform an initial cross-correlation by means of normal distributions overlapping at the tails. Also, it has been shown that virtually all signals may be represented with just 3-6 parameters, whereby the increase in discrimination from 3 (e.g. R, G, B) to 6 is minimal in practical terms (Jones et al., 2000). Ongoing work will also show that chromatic processing may yield an approximation of the information content of a data source (its entropy).

Multiple domains

For example, time, frequency, and spatial distribution, are suitable for concurrent chromatic processing and can aid cross-correlation of system behaviour, if required. It may be shown that this approach contributes more than alternative techniques such as the more limited (single domain) cases of Fourier analysis and wavelet analysis.

Multiple sources

Chromatic processing may be applied across the spectrum, e.g. directly to data from acoustic/visual/optical-fibre sensors, which again may assist cross-correlation of the holistic picture of system behaviour, or even directly to derived sources in the information domain, e.g. to financial information.

Transparency

Compared with some AI techniques such as neural nets, for example, chromatic processing directly supports traceability of the characterisation of system behaviour.

In summary, chromatic analysis is useful as an interdisciplinary bridge or metaphor for investigating diverse complex systems and consolidating the range of information about system behaviour that is available, from direct physical parameters through to holistic system overviews. Also, its polar plots may be useful as an intermediate human interface to complex system behaviour. Chromatic processing can produce a qualitative characterisation of a system (behavioural trajectory) and additionally quantify this using, for example, secondary HLS analysis and deriving event probability measures (Zhang et al., 2005).

5. Conclusions

The technology drive is enabling greater system complexity to be achieved, which increases demands on the use of, and integration of, technology in society. The requirements for holistic and intelligent monitoring increase accordingly. The long-term aims of intelligent monitoring systems are to characterise and assure current system behaviour and advise when intervention will be required. It may be demonstrated that chromatic monitoring, based on Gabor transform theory, statistics, filtering and colour science, analogous to human vision, meets the criteria that may be expected of intelligent monitoring systems for holistic application to complex systems, in particular by addressing data and information about the systems from the full range of their domains and sources. This suggests that chromatic processing is suitable for addressing complex systems that involve both machine and human behaviour in a holistic way, with a high degree of automation. In particular, application of intelligent chromatic monitoring to human and information-based domains is expected to be a growth area.

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